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Effects of Longwall Mining on Hydrology, Leslie County, Kentucky Part 2: During-Mining Conditions

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Mission Statement

The Kentucky Geological Survey at the University of Kentucky is a State-mandated organization whose mission is the collection, preservation, and dissemination of information about mineral and water resources and the geology of the Commonwealth. KGS has conducted research on the geology and mineral resources of Kentucky for more than 150 years, and has developed extensive public databases for oil and natural gas, coal, water, and industrial minerals that are used by thousands of citizens each year. The Survey's efforts have resulted in topographic and geologic map coverage for Kentucky that has not been matched by any other state in the Nation.

One of the major goals of the Kentucky Geological Survey is to make the results of basic and applied research easily accessible to the public. This is accomplished through the publication of both technical and nontechnical reports and maps, as well as providing information through open-file reports and public databases.

Effects of Longwall Mining on Hydrology, Leslie County, Kentucky
Part 2: During-Mining Conditions

Shelley Minns Hutcheson[1], James A. Kipp[2], James S. Dinger[1], Lyle V.A. Sendlein[2], Daniel I. Carey[1], and Gregory L. Secrist[1]

Abstract

The effects of longwall coal mining on hydrology in the Eastern Kentucky Coal Field are being investigated. The study area is in the Edd Fork watershed in southern Leslie County, over Shamrock Coal Company's Beech Fork Mine. Longwall panels approximately 700 ft wide are separated by three-entry gateways that are approximately 200 ft wide. The mine is operated in the Fire Clay (Hazard No. 4) coal; overburden thickness ranges from 300 to 800 ft. Mining began in panel 1 in September 1991 and concluded with panel 8 in September 1994. Long-term monitoring consisting of a network of piezometers and time-domain reflectometry (TDR) cables previously installed over panel 7, in conjunction with a continuously recording rain gage and flume, is continuing after the completion of mining.

Mining in panel 5 affected water levels in three of 24 piezometers installed over panel 7; the level went down in one piezometer and rose in two. Mining in panel 6 affected 16 of 24 piezometers; the level went down in 11 piezometers and rose in five. Mining in panel 7 affected water levels in 20 of 24 piezometers. Different water-level responses were recorded as the mine approached and passed by the instrumented sites. Thirteen piezometers failed as a result of undermining. These piezometers penetrated the zone of deep fracturing that extends upward approximately 450 ft (or 60 times greater than the mined thickness) above the mine. Only one piezometer showed a net increase in water level as a result of mining.

Mining-induced surface fractures, observed along roads in the watershed, were generally parallel to the slope of the land surface or mining direction and probably contributed to ground-water recharge. The surface stream was unaffected until it was undermined by panel 8; then the stream went dry.

TDR cables in the Hazard coal zone were deformed as mining passed by on the adjacent panel. Water levels in piezometers in the Hazard coal zone declined at the same time. TDR cables broke completely twice. The deepest complete break was in the Hazard coal zone and occurred when the active mine face was approaching, but still approximately 1,000 ft away from, the affected cable in panel 7. This corresponds to an angle of influence of 60 to 70°. Rock broke in the shallow subsurface (less than 50 ft deep) when the cable was directly undermined.

Water-level responses in piezometers adjacent to mining are related to the complex flow system, rather than a defined angle of hydrologic influence. Coal beds and other conductive strata transmit water-level responses as far away as 1,450 ft, whereas nonconductive strata transmit little water-level change at closer distances. The water-level responses observed in this study support existing subsidence models. Piezometers in the zone of intensive fracturing failed as a result of rock breakage. An aquiclude zone developed in the ridge. The integrity of strata and piezometers was generally maintained. The most variable effects were observed in the zone of surface fracturing, within 50 ft of the surface.

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Introduction

In longwall underground mining, a working face several hundred feet wide is advanced between parallel headings, producing a series of large, rectangular, mined-out panels. The face is temporarily supported by movable hydraulic jacks while the coal is being extracted. As these supports advance with the face, the unsupported roof fractures into blocks that collapse into the mined-out area. The remaining overburden then subsides onto this rubble.

The subsidence affects the hydrology of the mined area, and can cause loss or interruption of water supplies, which is a concern of both mine operators and adjacent landowners. This report summarizes findings from July 1993 through September 1994 for an ongoing investigation of the hydrologic effects of longwall mining in eastern Kentucky. The impetus for the study came from the Hydrology Steering Committee, formed to implement parts of a settlement agreement between the National Wildlife Federation and the U.S. Office of Surface Mining and the Kentucky Department for Surface Mining Reclamation and Enforcement. The agreement directs that the hydrologic regime of Kentucky's coal fields be more fully characterized to assist the regulatory agencies in meeting their hydrologic protection mandates.

The Edd Fork watershed, in southern Leslie County, in the Helton 7.5-minute quadrangle, was chosen for study (Fig. 1). This area is included in the Eastern Kentucky Coal Field, a hilly to mountainous region characterized by narrow, winding ridges, V-shaped valleys, and high topographic relief. The study watershed is drained by Edd Fork, a first-order tributary of Trace Branch. Trace Branch flows into Beech Fork, a major tributary of the Middle Fork of the Kentucky River. The Edd Fork Basin is located approximately midway between Beech Fork and the Middle Fork of the Kentucky River. These are third- and fourth-order streams, respectively, which represent local base level. Elevations in the Edd Fork watershed range from about 2,160 ft on the ridgetops to about 1,550 ft at the mouth of Edd Fork. Terrain in the watershed is steep; slopes average 26°. Surface mining has previously taken place here.

Phase 1 of the study (Minns and others, 1995) characterized the study area before mining took place so that the impact of future mining could be evaluated. This second phase of the study evaluates hydrologic responses to undermining of the Edd Fork watershed. During phase 3, the watershed will continue to be monitored after mining is completed.

This second phase will (1) evaluate the immediate hydrologic effects attributable to the undermining of panels adjacent to and beneath the instrumented site and (2) identify potential hydrologic impacts resulting from undermining in steep-slope terrain. Supporting data for this report are available in Minns and others (1996). Information on piezometer construction, water levels, and water quality are available from the Kentucky Ground-Water Data Repository at the Kentucky Geological Survey (see Appendix A for record identification numbers).

Site Investigation

The Edd Fork watershed was undermined by Shamrock Coal Company's Beech Fork Mine, operating in the Fire Clay (Hazard No. 4) coal bed. Overburden thickness in the watershed ranges from about 300 ft in the valley bottom to about 800 ft on the ridgetops. The configuration of the mine is shown in Figure 2. Mining was by longwall-mining methods, and occurred in 700-ft-wide panels. The panels were separated by 200-ft-wide, three-entry gateways developed by conventional room and pillar methods.

The mine began operation with panel 1 in April 1991 and ended with panel 8 in September 1994. Mining directly below the watershed was intermittent, as the active mine face moved in and out of the Edd Fork watershed during mining of panels 5 through 8. Mining under the watershed began with panel 5 in late August 1993 and continued until the mining ceased in September 1994.

Three sites over panel 7, representing the valley side (site A), ridgetop (site B), and valley bottom (site C), were selected for monitoring (Fig. 3). Each site contains a core hole and a closely spaced piezometer nest. Sites A and B are approximately along the centerline of panel 7, about 1,450 ft from the northern edge of panel 5; site C is approximately 100 ft off the centerline of panel 7, in the quarter of panel 7 closest to panel 8, and consequently is about 100 ft farther away from earlier mining than sites A and B (Fig. 4).

Effects of mining on water levels in piezometers are described in this report in relation to perpendicular reference planes (see Figure 4). If the mine face had not yet crossed this perpendicular plane, the mine was considered to be advancing on or approaching a site. If the active face had crossed this plane, the mine was considered to have passed by the site.

Previous Work

Phase 1. An NX-size core hole was drilled at each site during the winter of 1991–92 to provide stratigraphic control for piezometer locations, evaluate the nature of fracturing, conduct pressure-injection tests, and install time-domain reflectometry instrumentation to evaluate

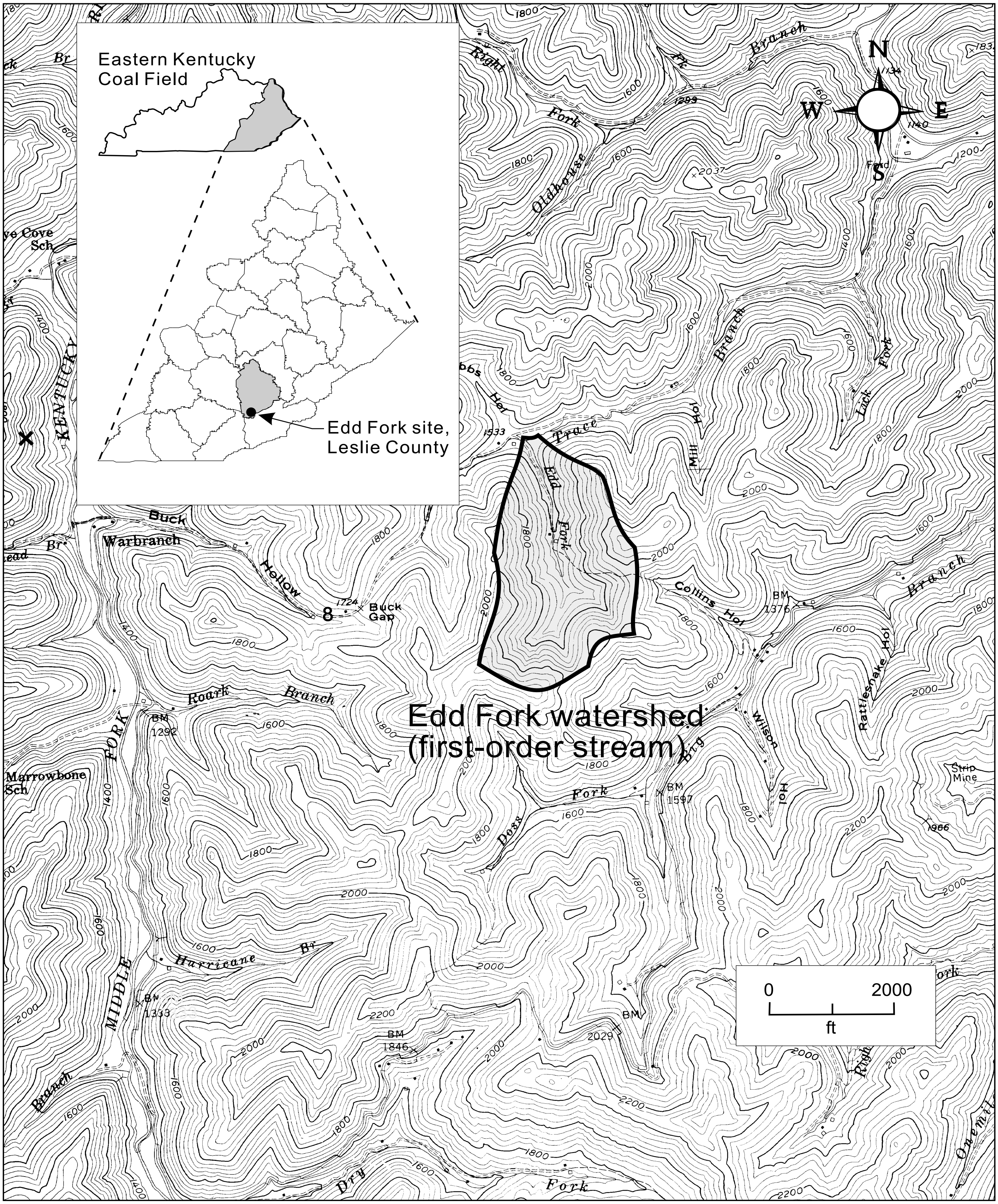

Figure 1. Location of the Edd Fork research area.

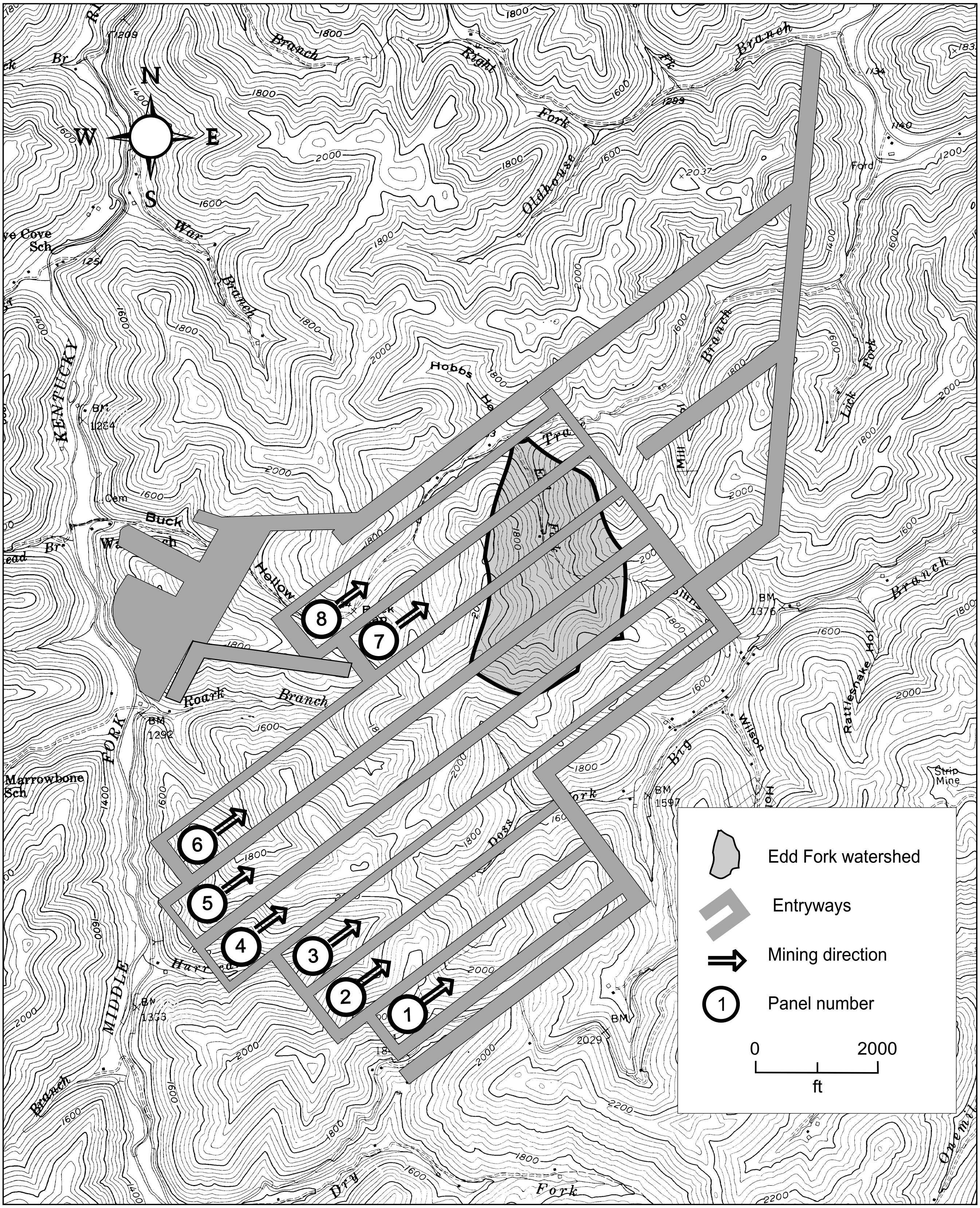

Figure 2. Configuration of the longwall mine in and surrounding the Edd Fork watershed.

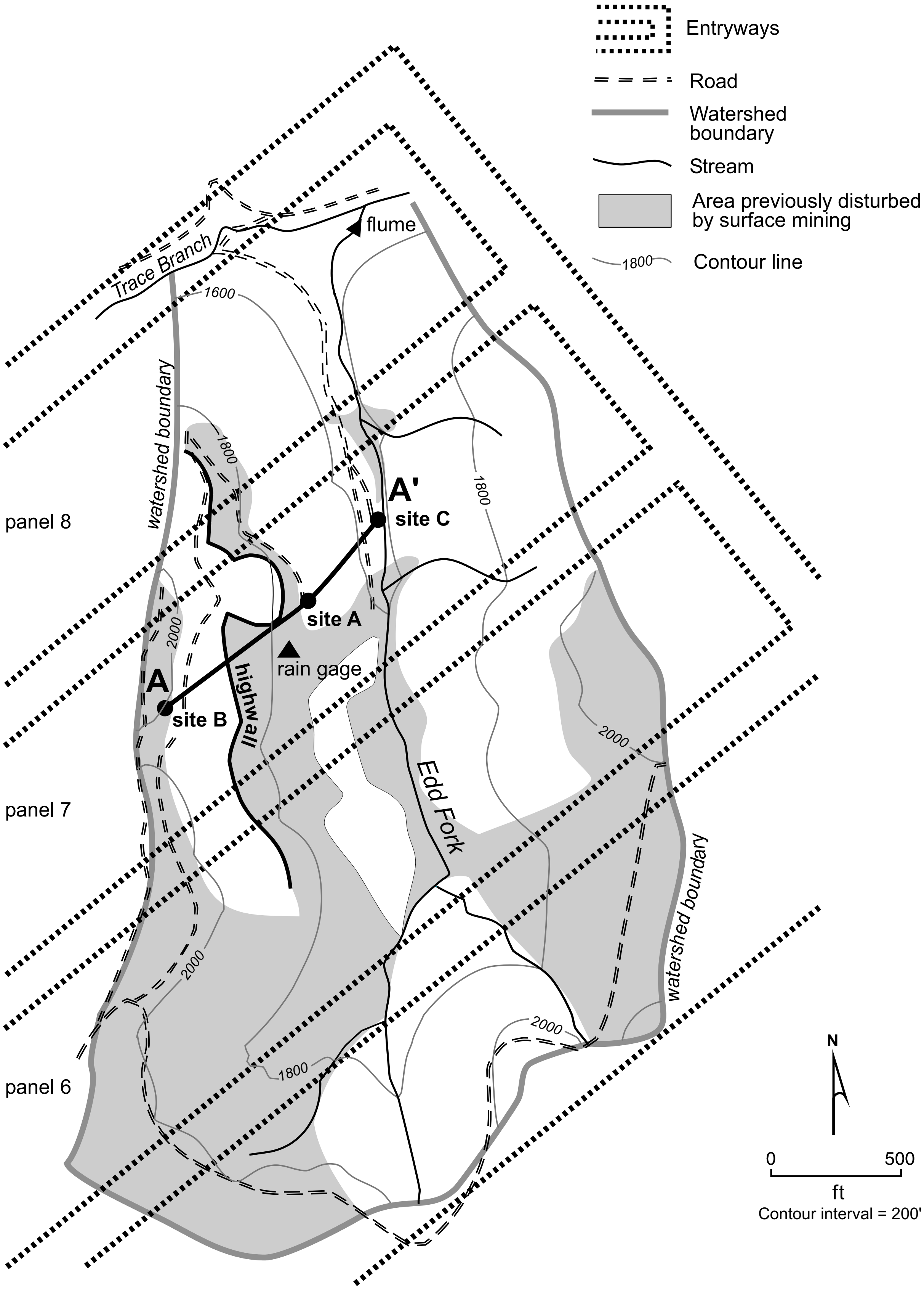

Figure 3. Locations of monitoring sites in the Edd Fork watershed. A–A' is line of section for Figures 5–6.

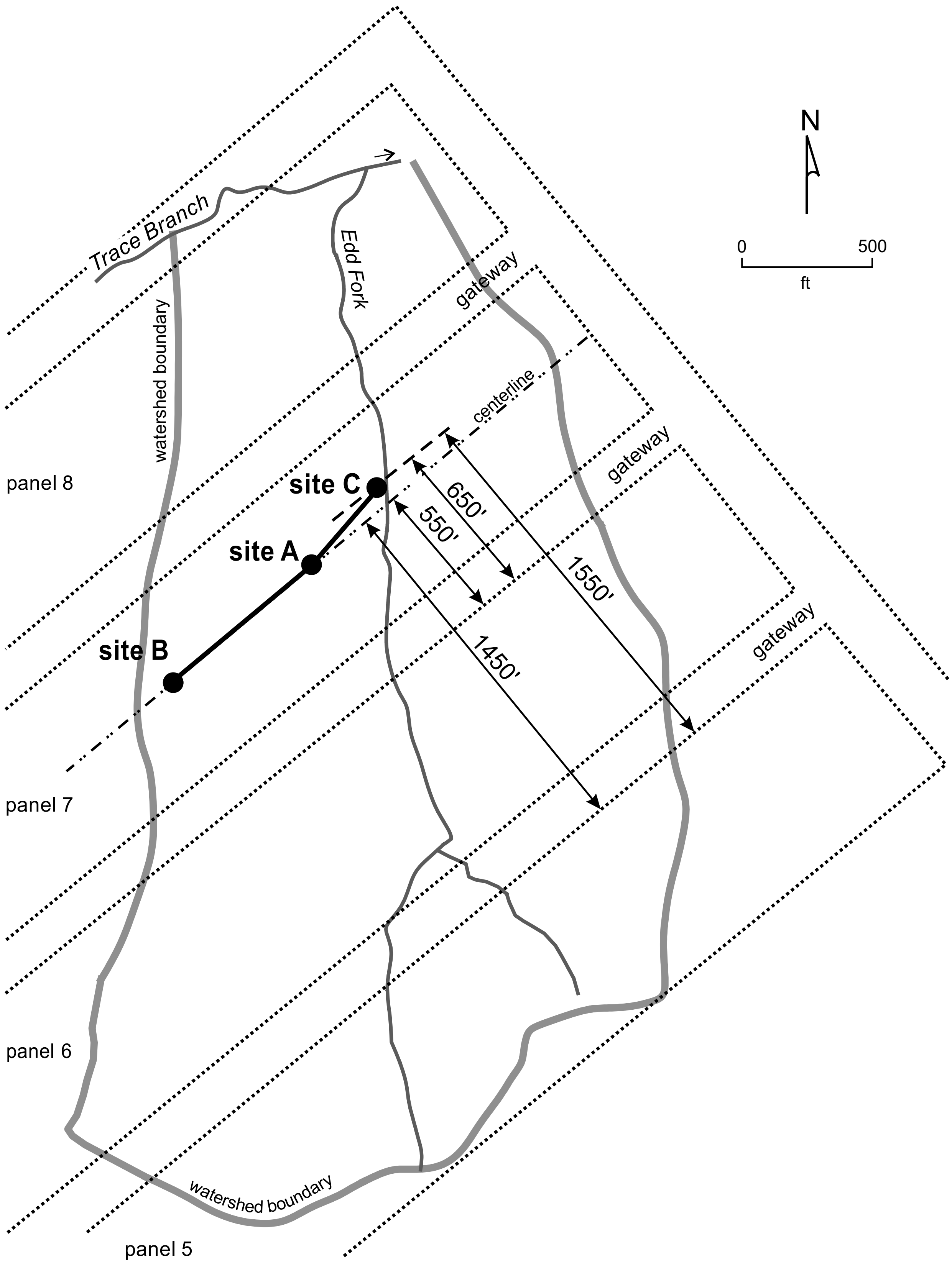

Figure 4. Distances from the edges of longwall panels 5 and 6 to the centerline of panel 7.

rock strain. Geologic cross section A–A' (Fig. 5) was constructed from these core data. General geology of the area was described by Rice (1975).

Twenty-four piezometers were completed in July 1992 to provide information on discrete stratigraphic zones in the topographic settings represented by the three sites (Fig. 6). Six of the piezometers were located at site A, ranging in depth from 35 to 417 ft. Twelve of the piezometers were installed at site B, ranging in depth from 67 to 684 ft. The remaining six piezometers were installed at site C, ranging in depth from 18 to 262 ft. A rain gage and flume were also installed in the study basin during the summer of 1992 to provide additional data for hydrologic analysis (see Figure 3).

Before mining began, Minns (1993) developed a conceptual model of ground-water flow in the basin. She differentiated three ground-water zones on the basis of fracture occurrence and hydraulic properties (Fig. 7). The shallow-fracture zone is made up of highly fractured strata that parallel the land surface to a depth of 50 or 60 ft. The elevation-head zone, located above drainage, is defined as the region where the head in a piezometer is approximately equal to the elevation of the midpoint of the piezometer's open interval. The pressure-head zone extends downward from the base of the elevation-head zone (or the shallow-fracture zone where the elevation-head zone is absent near valley bottoms). The study area can also be divided into two distinct freshwater geochemical facies. Shallow water is a calcium-magnesium-bicarbonate-sulfate type, and deeper water is a sodium-bicarbonate type. See Minns and others (1995) for a more thorough description of the geochemical facies.

A Model of Subsidence Effects. Fracturing and sagging of strata caused by subsidence over mined panels generally lead to increases in hydraulic conductivity and storativity that can alter ground-water flow patterns. In many cases, wells, springs, and surface streams are affected. Coe and Stowe (1984) developed a hydrologic model of subsidence zones resulting from longwall mining. The area immediately above the mined panel caves into the void created by the extraction of the coal. This completely caved rubble zone extends above the mined panel as much as four to six times the extracted thickness.

Above the totally caved zone, a transitional zone of highly fractured rock can reach as much as 30 to 60 times the extracted thickness above the base of the void. This zone is characterized by extensive vertical fracturing and some massive block-type caving. Wells completed in either of the fractured zones normally fail because water can rapidly drain directly to the mine works. Little recovery of water levels can be expected until the mine is allowed to flood after the completion of mining.

If the mine is at sufficient depth, there may be an additional zone above the extensively fractured bedrock in the subsidence trough. Most of the rock movement in this zone is apparently minor horizontal slippage between strata. As a result, the strata in this zone tend to act as a "composite beam," and the integrity of low-permeability layers is generally maintained during subsidence. These intact layers tend to limit the downward movement of ground water to the mine void and cause this zone to serve as an aquitard when it is present. Water levels in wells completed in this zone may temporarily decline slightly because of an increase in porosity, but they often subsequently recover to near pre-mining levels.

Near-surface strata (generally at depths up to about 50 ft) are susceptible to fracturing and movement during subsidence. Although water levels in shallow wells often decline slightly because of increases in porosity and permeability associated with subsidence, these changes may actually result in an increased availability of ground water from dewatering, often with precipitous water-level declines in the fractured zone.

Methodology

Water-Level and Precipitation Measurement

Water levels in piezometers were measured every 2 weeks from the time of installation through the end of 1992, and then monthly through 1993. Weekly measurements were taken while mining took place in panels 6 and 7 (January 1994 to mid-May 1994). Daily water levels were recorded when the instrumented sites were actually undermined (May 16, 1994, through June 18, 1994). Weekly measurements resumed during mining of panel 8 (June 23, 1994, through September 1994).

A tipping-bucket rain gage connected to a digital data logger has been recording precipitation in the Edd Fork watershed during the study period. Streamflow data were recorded on Edd Fork approximately 30 ft upstream from its confluence with Trace Branch at 10-min intervals using a pressure transducer and a Telog[1] data logger installed in a 3-ft-deep fiberglass H-flume.

[1]The use of manufacturer and trademark names does not constitute an endorsement of the product by the Kentucky Geological Survey or the University of Kentucky; the names are included for reference only.

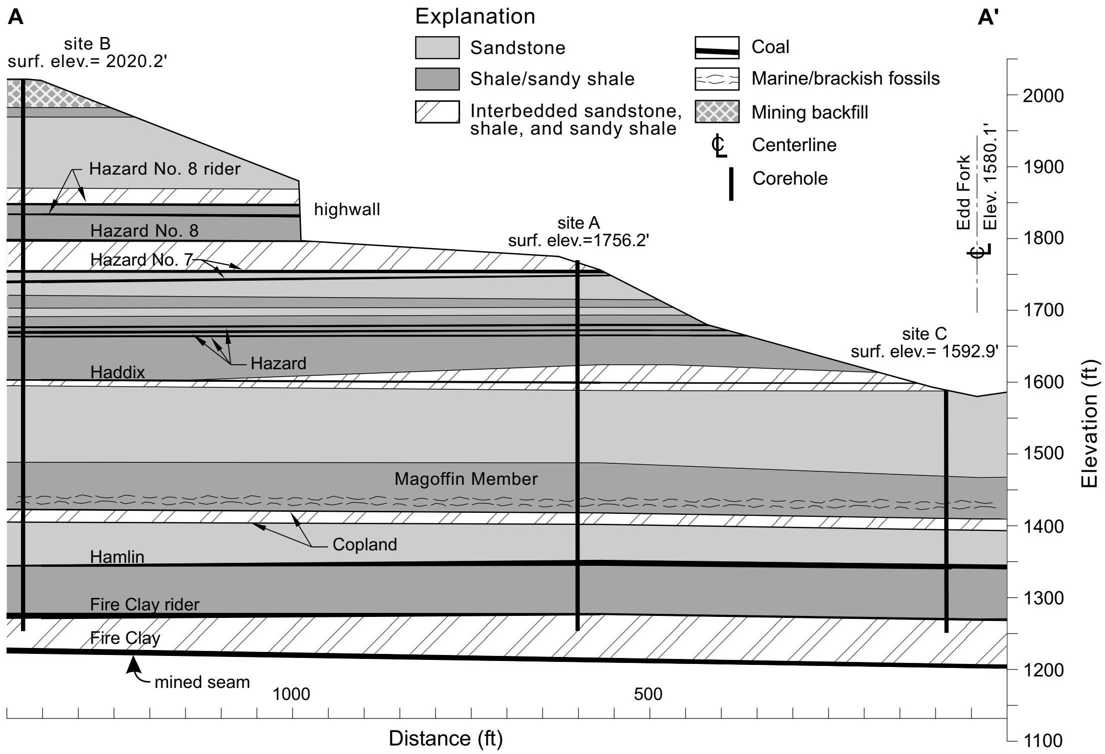

Figure 5. Geologic cross section along the centerline of panel 7, constructed from core-hole data. From Minns and others (1995, Fig. 7).

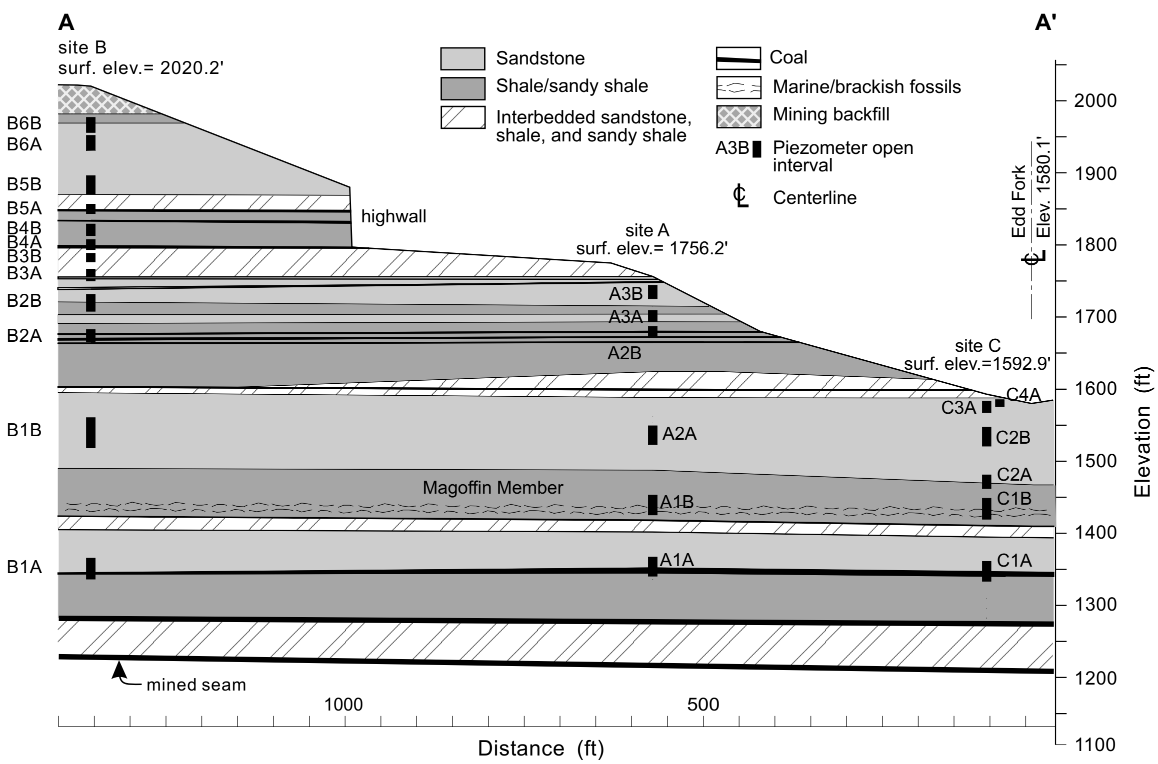

Figure 6. Locations of piezometers installed over panel 7 and used in the pre- and during-mining phases of the project. From Minns and others (1995, Fig. 12).

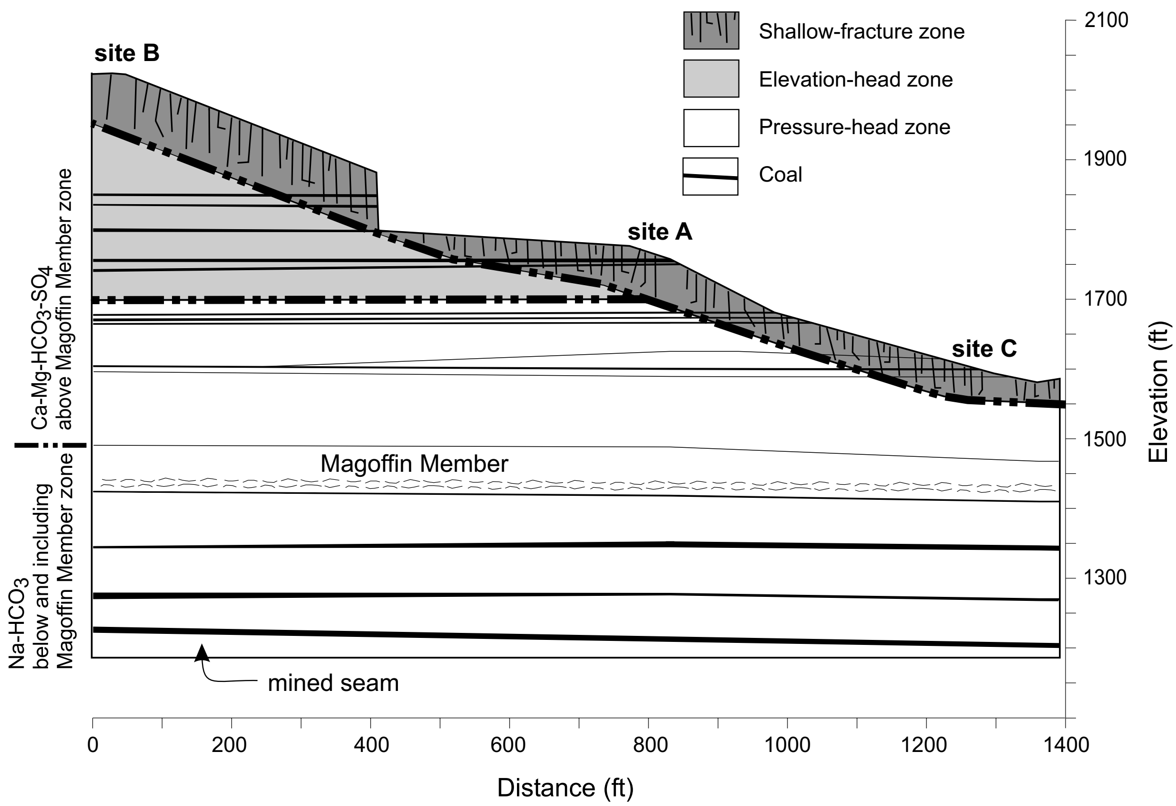

Figure 7. Locations of hydraulic and chemical ground-water zones (after Minns, 1993).

Time-Domain Reflectometry

Time-domain reflectometry (TDR) was used to document rock deformation related to subsidence (Bauer and others, 1991). See Minns and others (1995, Appendix B) for an explanation of time-domain reflectometry.

Coaxial cables were installed in the three core holes at sites A, B, and C. The holes were subsequently backfilled with an expansive grout to bond the cable to the surrounding rock. Changes in the distance between the inner and outer conductors of the cable, breaks in either conductor, or shorts between the conductors produced changes in TDR waveforms, which could be used to determine the location and nature of the deformation.

Baseline electrical measurements were taken at the sites on October 5, 1993, and February 15, 1994. Weekly measurements began in March 1994, while panel 6 was being mined. Daily TDR readings were taken as mining approached the instrumented sites in panel 7, and continued until each cable broke near the ground surface.

Observation of Surface Fractures

Surface fractures were observed along roads and other nonvegetated areas in and around the Edd Fork watershed at various times throughout the mining of panels 5 through 7. The approximate orientations and locations of these fractures were mapped and described. In some cases, individual fractures were noted; in other areas, the features were zones of multiple fractures. Heavy vegetation precluded mapping fractures that may have occurred in other parts of the watershed.

Results of Mining Effects

The most obvious measure of the effects of mining was changes in water-level responses in piezometers. For piezometers that stabilized rapidly after installation, pre-mining data were collected from August 1992 through June 1993. This interval was not long enough to demonstrate long-term water-level variations that might occur from year to year, however.

Several piezometers located in low-conductivity strata apparently remained in transient conditions throughout the pre-mining period, either because of the effects of purging (A1B, B1B, B3B, B4B, C1A, and C1B) or because of natural equilibrium processes (B1A). If water-level changes were markedly different from predictable purge-recovery trends in low-conductivity zones, the changes were interpreted to be mining-related.

Measurement frequency varied throughout the monitoring period from daily to monthly. Longer measurement intervals tend to smooth out data spikes that might otherwise be apparent in more closely spaced measurements.

In general, observed water-level changes were considered to be mining-related if an apparent trend coincided with the approach or retreat of the mine face and if the magnitude or duration of the water-level change was more or less than previously observed comparable seasonal values.

The Edd Fork watershed, located near the northeastern end of panels 5 through 8, was intermittently undermined from late August 1993 through mid-September 1994 (see Figure 2). During half this period, the active face was outside the watershed. While mining was taking place in the first 4,100 ft of panel 5 and the first 3,600 ft of panel 6, it was isolated from much of the above-drainage strata in Edd Fork by Roark Branch, a deeply incised stream that is roughly perpendicular to mining direction. The stream valley is incised to the top of the sandstone that overlies the Magoffin Member on panel 5 (Fig. 8) and to the bottom of this sandstone in panel 6 (Fig. 9). Until mining crossed into the watershed in panel 5 in July 1993 and in panel 6 in December 1993, no effects to overlying strata were likely that were directly attributable to the currently active mining. When the active face was out of the watershed, however, water levels potentially had an opportunity to reequilibrate to head conditions in the surrounding strata, especially after mining on panel 5. In addition, there were delayed effects, probably caused by mining in panel 5, that became apparent while the mining in panel 6 was ongoing but was too distant to directly affect the above-drainage strata in the watershed.

Water-level responses to mining were related to the hydraulic behavior of the strata in which a piezometer was located: specifically, relative hydraulic conductivity and whether the piezometer was in the shallow-fracture zone, the elevation-head zone, or the pressure-head zone (Minns and others, 1995). Many piezometers are located in similar lithologies (for example, above-drainage coal beds) or in the same stratigraphic interval in different topographic settings (for example, the Magoffin Member).

All water-level measurements before and after mining were taken relative to the top of the piezometer casing. Water levels measured in piezometers after the mine face passed beneath them in panel 7 do not represent their true elevation. Approximately 4.5 and 7.5 ft of surface subsidence occurred at the two sites on the mountain (sites A and B) and valley bottom (site C), respectively, as the mine face passed beneath panel 7. Piezometer casings remained attached to the rock into which they were grouted, and many casings sheared and failed at depth when the mine face passed, indicating that the wells reacted with the rock and not as independent entities with regard to rock subsidence. Therefore, for simplicity and in order to relate water levels to pre-mining hydrostratigraphic position, water-level elevations taken after the passage of the mine face in panel 7 and presented in hydrographs and charts do not reflect true elevation, but are relative to pre-mining stratigraphic position.

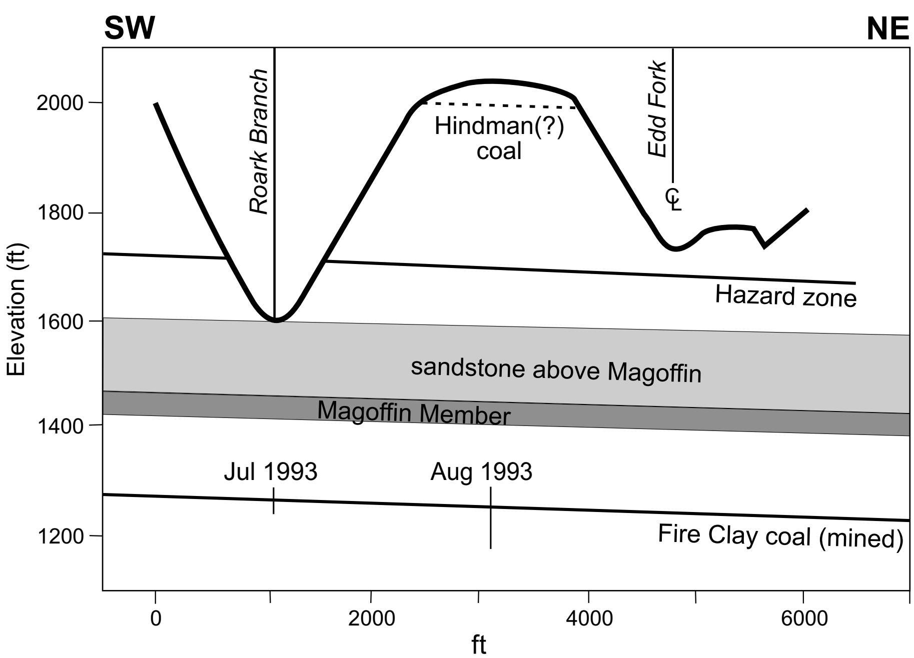

Figure 8. Cross section along centerline of panel 5, showing how Roark Branch Valley isolates strata mined in the southwestern ends of the longwall panels from strata in the Edd Fork watershed.

Piezometers in the Shallow-Fracture Zone

Five piezometers are located in the shallow-fracture zone (Fig. 6). Piezometer B6B is located on the ridgetop, and piezometers A3A and A3B are located on the valley side. Two other piezometers, C3A and C4A, are located in the valley bottom. Piezometers B6B and A3B were dry throughout the study period. The hydrographs shown in Figures 10 and 11 illustrate the response to mining for piezometers in the shallow-fracture zone that had measurable amounts of water.

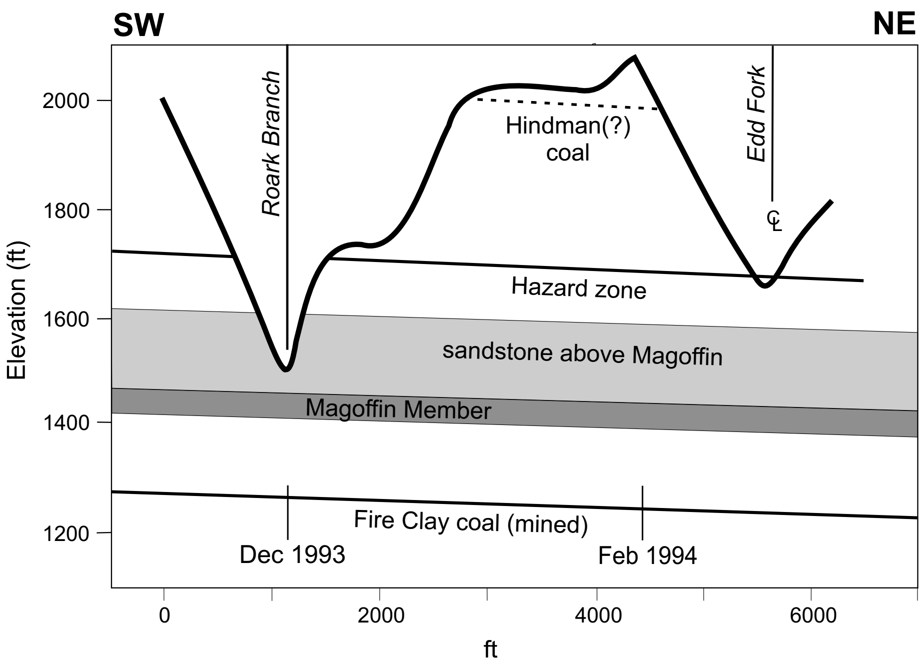

Figure 9. Cross section along panel 6, showing how Roark Branch Valley isolates strata mined in the heads of the longwall panels from strata in the Edd Fork watershed.

Table 1 summarizes water-level responses in these piezometers as the active face approached and retreated on panels 5 through 8. The net effect of mining on each piezometer in the shallow-fracture zone is summarized in Table 2.

Piezometers in the Elevation-Head Zone

Eight piezometers are located in the elevation-head zone, all in the ridgetop setting (Fig. 6). Two piezometers (B6A and B5B) are completed in a sandstone unit that caps the ridges in the area. Three piezometers (B5A, B4A, and B3A) are in different coal beds in the upper part of the ridge, and three piezometers (B4B, B3B, and B2B) are in strata between the coal beds. Figures 12 through 14 are hydrographs illustrating the water-level responses for these piezometers in the elevation-head zone. Table 3 summarizes water-level responses that occurred in these piezometers before and during mining. The net effect of mining on each piezometer in the elevation-head zone is summarized in Table 4. Only piezometer B6A (Fig. 12) had a net increase in water level compared to pre-mining conditions. The casing for the deepest piezometer (B2B) (Fig. 14) failed as a result of undermining. The casing for piezometer B6B, which was dry throughout the study, also failed as a result of undermining.

Piezometers in the Pressure-Head Zone

Eleven piezometers are located in the pressure-head zone, and represent all three topographic settings and four stratigraphic intervals (Figs. 6–7). Piezometers A2B and B2A are located in the Hazard coal, the uppermost coal bed in the pressure-head zone, and are the only above-drainage piezometers in the pressure-head zone. Four piezometers (B1B, A2A, C2A, and C2B) are located in the sandstone unit overlying the Magoffin Member, a relatively impermeable marine shale. Two piezometers (A1B and C1B) are located in the Magoffin Member. The deepest piezometers (B1A, A1A, and C1A) span an interval that includes the Hamlin coal bed. Figures 15 through 18 are hydrographs illustrating the water-level responses for these piezometers in the pressure-head zone. The large downward spikes in the hydrograph for piezometer C1A (Fig. 18) represent purging prior to water-quality sampling. Table 5 summarizes water-level responses that occurred in these piezometers before and during mining. The net effect of mining on each piezometer in the pressure-head zone is summarized in Table 6. There was a net decrease in head, compared to pre-mining conditions, for all piezometers for which trends could be determined. In addition, the casing failed for all piezometers in this zone.

Summary of Piezometer Responses by Panel

Mining on each panel caused a variety of responses. Table 7 shows whether the water level went up, down, or fluctuated, or whether the piezometer failed for each piezometer as mining either passed by the instrumented sites (panels 5 and 6) or went under them (panel 7).

Mining in panel 5, located approximately 0.25 mi away from the centerline of panel 7, produced observable water-level responses in three of the 24 piezometers in the study area. No piezometers in the shallow-fracture zone were affected. The water level in piezometer B5B, located in the ridge-capping sandstone in the elevation-head zone, went down as the mine face passed site B (Fig. 12). The water levels in both piezometers in the Hazard coal bed (A2B and B2A) in the pressure-head zone went up as the mine face passed each site (Fig. 15).

Mining in panel 6, located about 550 ft from the centerline of panel 7, affected 16 of the 24 piezometers. Of these 16 piezometers, the water level went down or

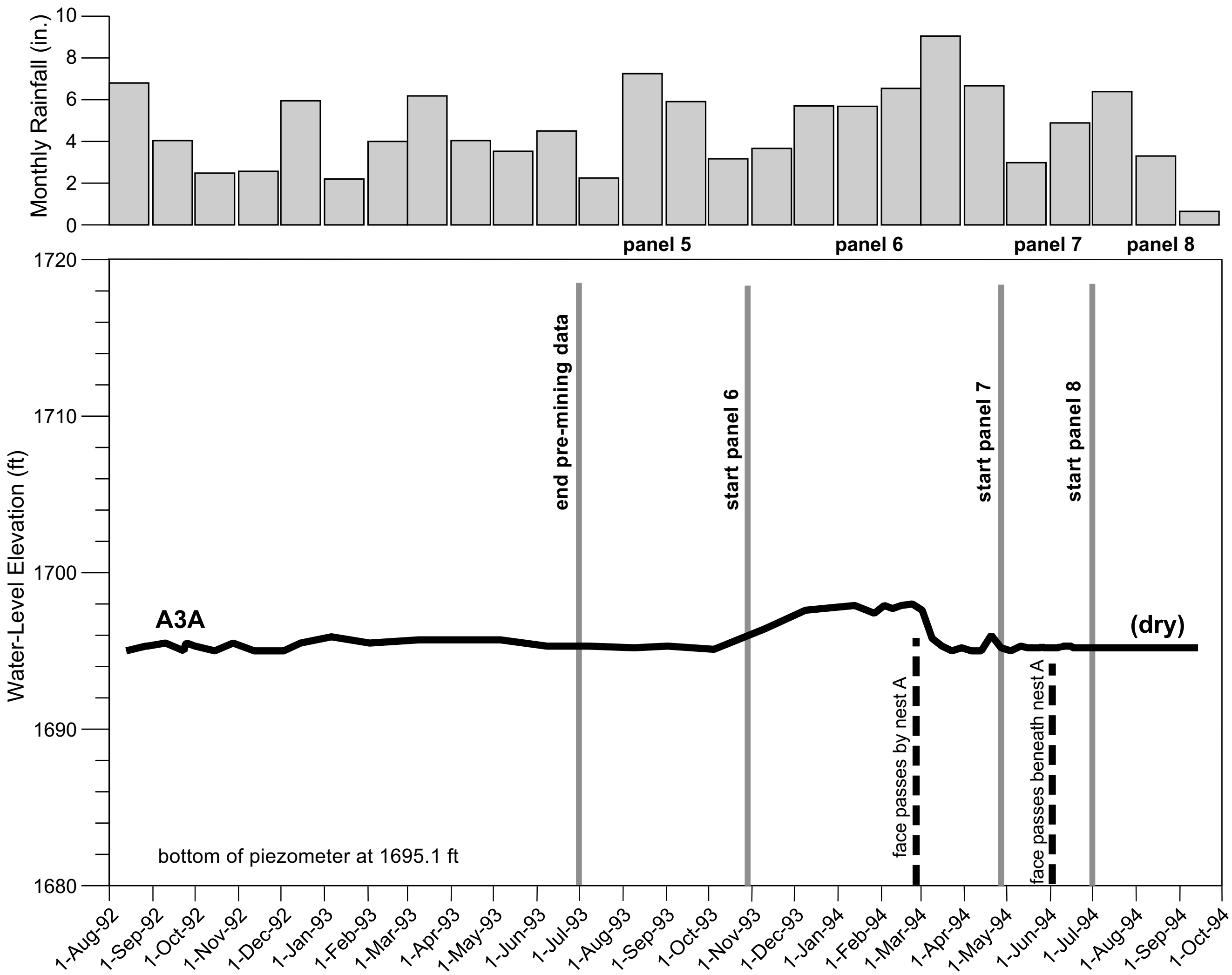

Figure 10. Hydrograph for valley-side piezometer A3A in the shallow-fracture zone.

the piezometer went dry in 11 of them and the water level went up in five of them (Table 7). Only one of five piezometers in the shallow-fracture zone was affected by mining in panel 6, but six of eight piezometers in the elevation-head zone and nine of 11 piezometers in the pressure-head zone were affected.

Mining in panel 7 had the most widespread impact on the piezometer network (Table 7): 20 of 24 piezometers responded in some manner when this panel was mined. Only one of the three water-bearing piezometers in the shallow-fracture zone was affected (water level went down); one dry piezometer failed structurally, however. Seven of eight piezometers in the elevation-head zone were affected by undermining in panel 7. All 11 piezometers in the pressure-head zone were affected by undermining in panel 7; all failed structurally, and water levels declined in eight of them before failure. Three piezometers that failed (two in the Magoffin Member and one that went dry from mining in panel 6) did not have a significant change in water level prior to failure.

Only 11 piezometers remained intact after mining was completed in panel 7. They were used to measure water-level changes during mining in panel 8. Water levels in piezometers generally were not affected by mining in panel 8, and remained at the same level after undermining in panel 7. The water level declined in one coal-bed piezometer (B4A) after the mine face passed by on panel 8.

Discussion

Subsidence Models and Ground-Water Zones

The overall response of the piezometers to undermining supports the subsidence model, based on Coe and Stowe (1984), shown in Figure 19. Numerous sur-

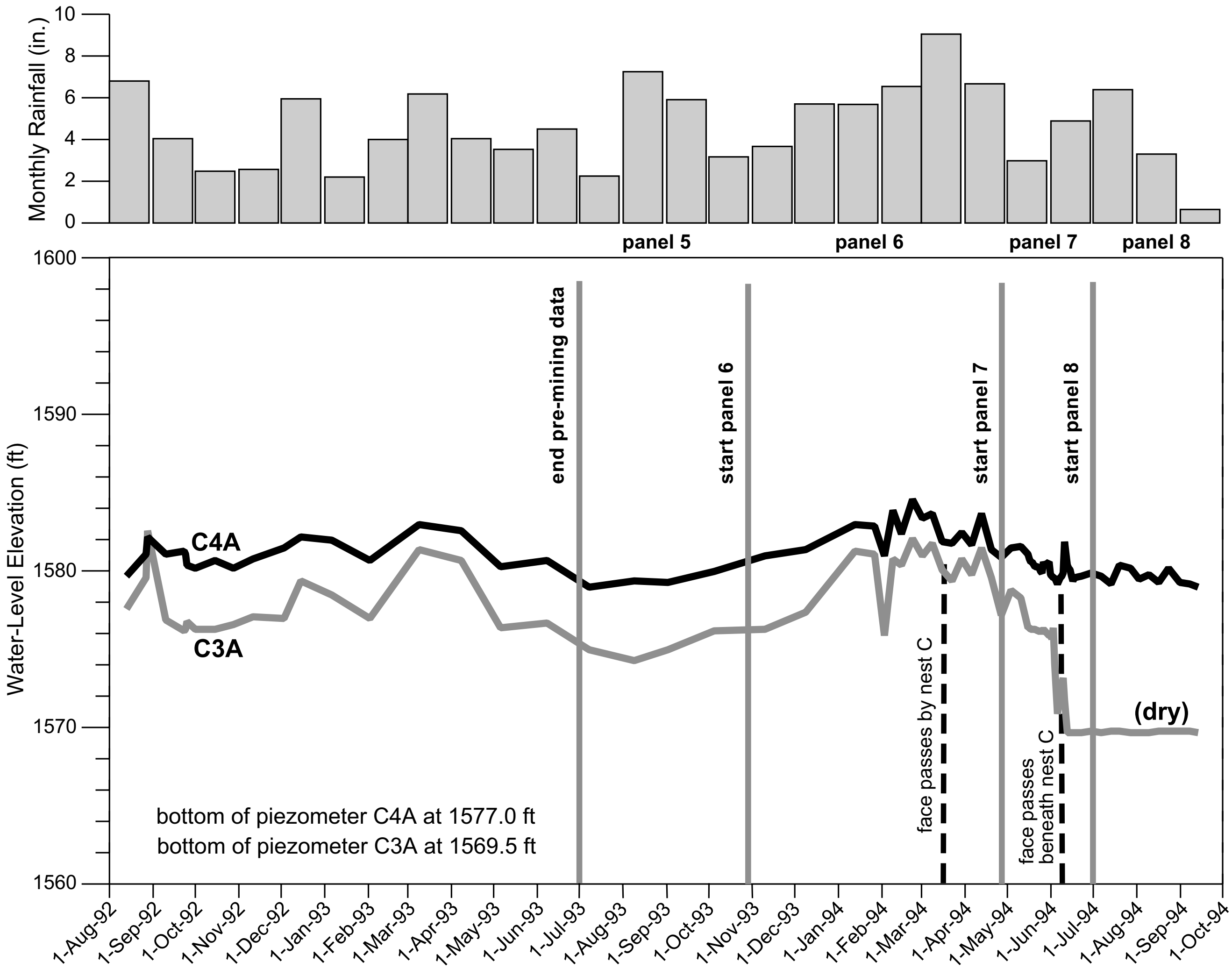

Figure 11. Hydrographs for valley-bottom piezometers C3A and C4A in the shallow-fracture zone.

face cracks were observed on the ground along roadways and other nonvegetated surfaces (Minns and others, 1995). The model presented by Coe and Stowe (1984) predicts that water levels will decline in this zone as a result of undermining. Two shallow piezometers (A3A and C3A; Figs. 10 and 11, respectively) were dewatered after a period of water-level fluctuation. A very shallow valley-bottom piezometer (C4A; Fig. 11), adjacent to piezometer C3A, was not dewatered, however. The variable response of similar piezometers indicates that the shallow ground-water system is complex and variably interconnected.

The aquiclude zone shown in Figure 19 generally coincides with the elevation-head zone of Minns's (1993) conceptual ground-water flow model. The casing failed during undermining in only one piezometer in this zone (B2B; Fig. 14), located at the very base of the zone. This piezometer was completed in a common hole that included a deeper piezometer completed in the zone of deep fracturing. Piezometric water levels in conductive strata either went up or down during undermining, whereas water levels in nonconductive strata showed no change. Because strata in the elevation-head zone are not pressurized and some coal beds may be only partially saturated, water-level increases or decreases in this zone must result from physical movement of water through pores or fractures, either from increased recharge or from compaction of existing fractures. Permeability in coal-field strata is generally fracture-derived; therefore, water-level changes were observed only in coal beds or fractured rock. Nonfractured strata did not transmit water rapidly enough for water-level changes to be evident. The lack of response in some piezometers in this zone indicates that there was mini-

Table 1. Response of piezometer water levels in the shallow-fracture zone to mining.

Location	ridge top	valley side		valley bottom	
Piezometer	B6B	A3A	A3B	C3A	C4A
Total Depth	64.0	65.6	33.5	24.0	17.0
Lithology	sandstone and shale	fractured sandstone	fractured sandstone	weathered sandstone	weathered sandstone
Pre-Mining (Prior to 7/1/93)					
Range of water-level fluctuations	dry	0.9	dry	6.4	2.8
Conductive strata	yes	yes	yes	yes	yes
Panel 5 (5/3/93 through 10/20/93)					
Range of water-level fluctuations	dry	< 0.5	dry	2.0	1.0
Water-level response—mine approach	none	none	none	none	none
Water-level response—mine retreat	none	none	none	none	none
Panel 6 (10/25/93 through 4/12/94)					
Range of water-level fluctuations	dry	3.0	dry	6.0	3.5
Water-level response—mine approach	none	up	none	none	none
Water-level response—mine retreat	none	dry	none	none	none
Panel 7 (4/18/94 through 6/26/94)					
Range of water-level fluctuations	dry	dry	dry	9.0	3.0
Water-level response—mine approach	none	none	none	fluctuate	none
Water-level response—mine retreat	none	none	none	dry	none
Panel 8 (6/30/94 through 9/14/94)					
Range of water-level fluctuations	dry	dry	dry	dry	2.0
Water-level response—mine approach	none	none	none	none	none
Water-level response—mine retreat	none	none	none	none	none
Up: Water level in well went up relative to previously described state Down: Water level went down relative to previously described state Fluctuate: Water level fluctuated, with no clear trend					

mal additional fracturing from mining that created interconnection between piezometers.

The zone of deep fracturing shown in Figure 19 corresponds with the pressure-head zone of Minns's (1993) conceptual ground-water flow model. All piezometers in this zone failed in an interval that was within approximately 60 times the extracted coal thickness. In general, water levels in piezometers in this zone declined significantly prior to piezometer failure. Only water levels in piezometers in the Magoffin Member did not decline as a result of mining. This indicates that fracturing may not have extensively penetrated the Magoffin Member; otherwise, water levels would have declined. Because strata in the pressure-head zone are pressurized, water levels can fall in response to pressure drops or in response to actual draining of the strata. Strata were probably dewatered in the lower part of this zone, as evidenced by gas blowing from deeper piezometers after failure.

Adjacent-Panel Responses

Because hydrologic responses were documented beyond reasonable angles of draw, mining in the adjacent panels must have exerted a hydrologic effect that

Table 2. Net effects from mining in the shallow-fracture zone.

Piezometer	*Net Response to Mining*
ridgetop B6B	 failed
valley-side A3A A3B	 went dry no change
valley-bottom C3A C4A	 went dry no change

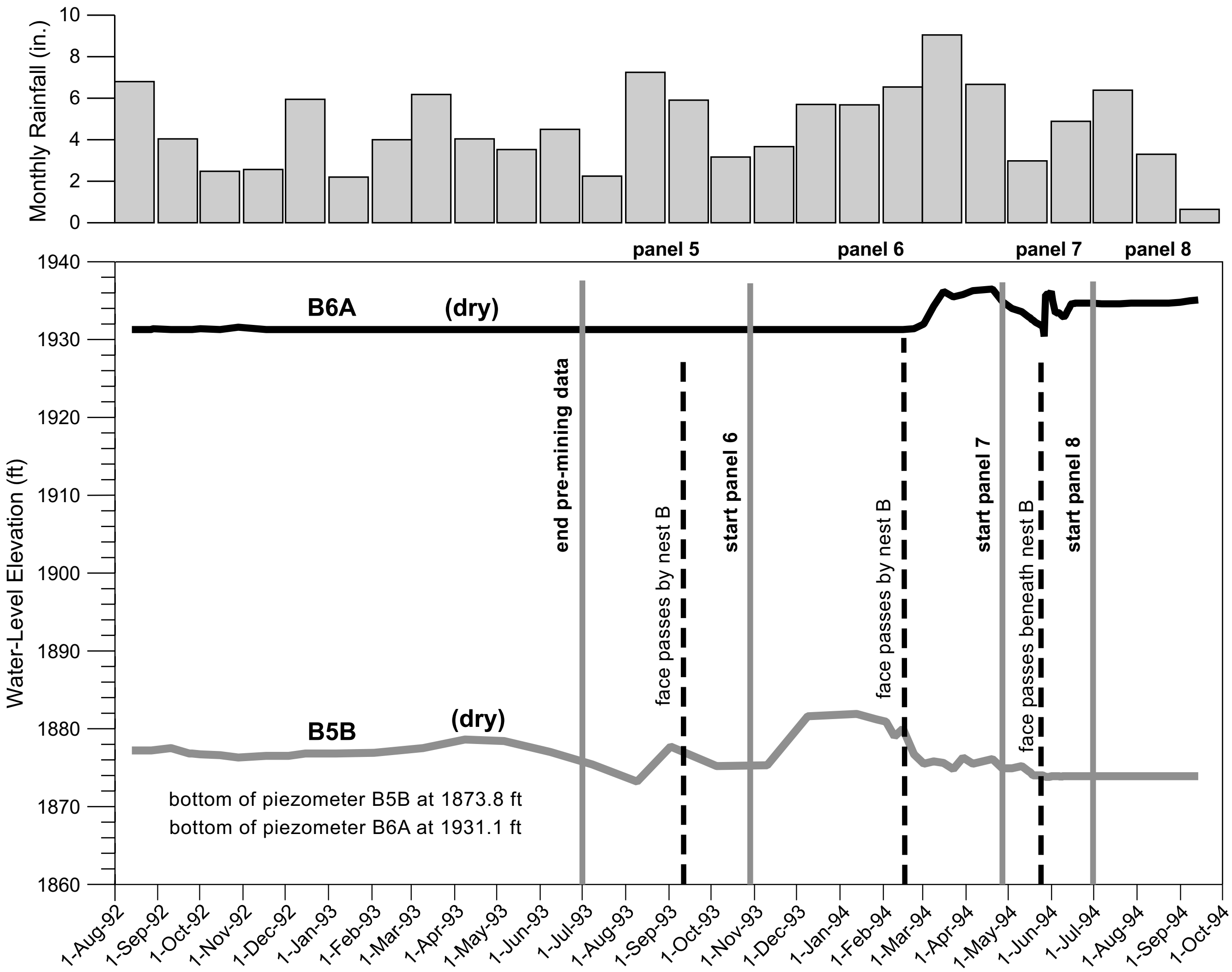

Figure 12. Hydrographs for piezometers B5B and B6A in the elevation-head zone.

extends beyond the probable area of surface subsidence. An angle of dewatering influence (Cifelli and Rauch, 1986) is defined as the angle between a vertical line projected upward from the rib or end of a longwall panel and the farthest point of dewatering effects from the longwall panel. Because closely vertically spaced piezometers at the site responded differently to mining in the adjacent panels, the extent of hydrologic influence is apparently dependent on hydraulic conductivity of the strata and interconnectivity of recharge and discharge zones, rather than on a single specific angle of dewatering influence beyond the edge of a panel.

Mining in adjacent panels did not generally affect piezometers located in the shallow-fracture zone unless the recharge area was affected by shallow fracturing caused by mine subsidence. In the case of piezometer A3A, shallow fractures over panel 6 probably enhanced recharge to the sandstone near the outcrop. A sustained water-level increase was observed in this piezometer after mining in panel 6 crossed Roark Branch. A subsequent decline occurred after mining passed the site in panel 7; the decline was probably the result of additional fracturing draining the stratigraphic interval.

Effects from adjacent-panel mining were fairly common, but variable, in the elevation-head zone, and were primarily the result of enhanced recharge reaching high-permeability zones such as coals or bedding surfaces and being transmitted laterally. For example, the likely angle of draw (25 to 30°) for panels 4 through 6 intercepted the recharge area for the ridge-capping sandstone at some point while mining was in or adjacent to the Edd Fork watershed. Infiltration to the base of this sandstone was enhanced by surface fractures that directed water to the interface of this sandstone with

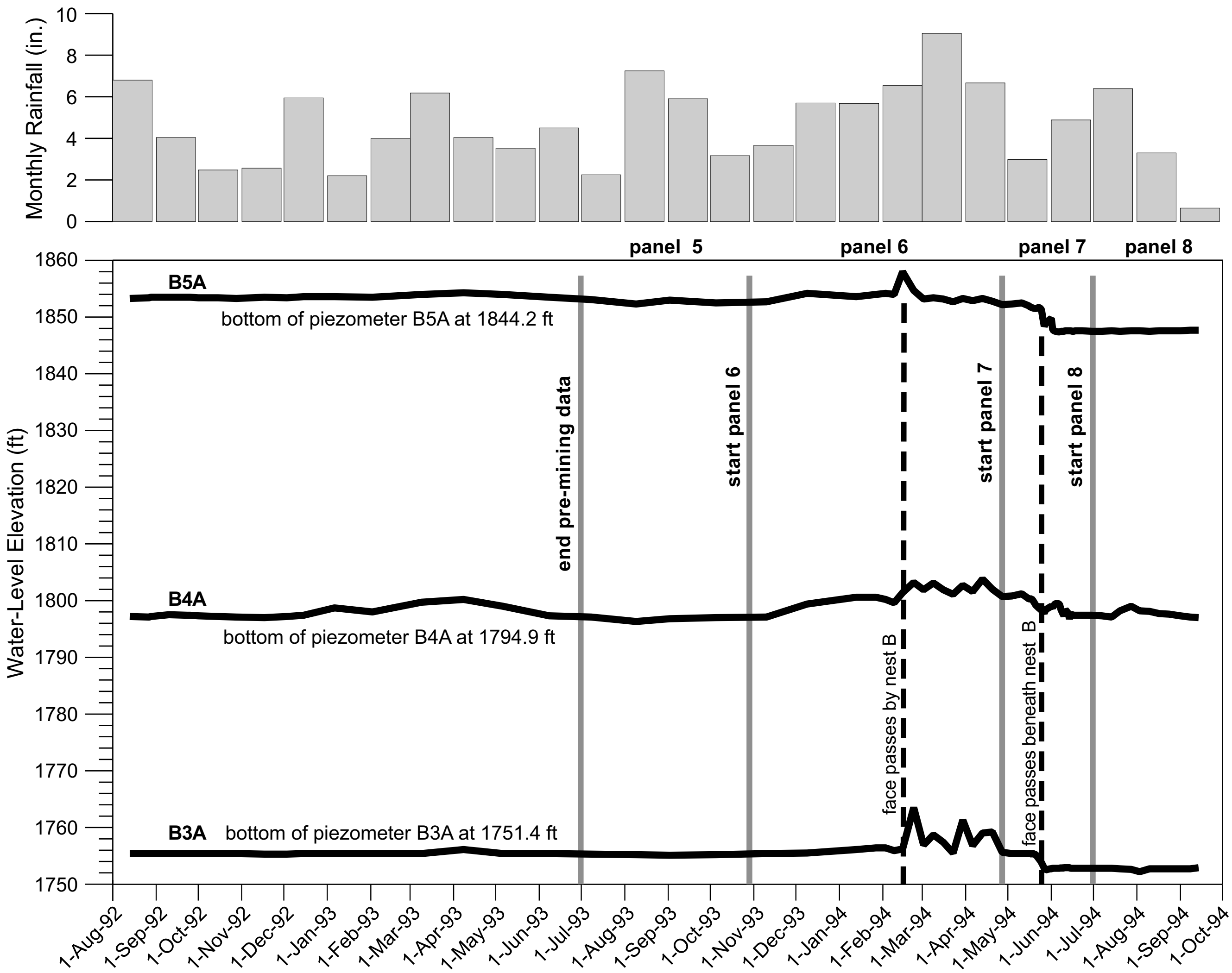

Figure 13. Hydrographs for coal-bed piezometers B3A, B4A, and B5A in the elevation-head zone.

the underlying shale. Water apparently either moved 0.25 mi along the bedding surface to piezometer B5B, or a water-pressure increase was transmitted over that distance through water-filled fractures (Fig. 12). Coal-bed piezometers B3A, B4A, and B5A were affected similarly (Fig. 13). Either coal-bed recharge increased as a result of fracturing near the surface and flowed horizontally within conductive coal beds, or compression of fractures over the mined panel transmitted transient changes in water levels.

The abrupt decline in water level in piezometer B5A after the active face in panel 6 passed indicates that fractures either dewatered the coal beds or that the compression phase of the face passage ended, returning the water level in this piezometer to previous levels. Strata between coal beds did not have extensive fractures to provide horizontal avenues of flow; therefore, piezometers B3B and B4B were unaffected by mining in panel 6 (Fig. 14). The water level in the deepest piezometer in strata between coal beds (B2B), located near the boundary of the zone of deep fracturing, began to fall in response to fracturing in the zone of deep fracturing over panel 6 (Fig. 14).

Effects from adjacent-panel mining were also common in the pressure-head zone. Water levels increased in piezometers B2A and A2B in the Hazard coal bed during mining in panel 5 (Fig. 15). The Hazard coal bed lies close to the land surface over much of the watershed, and fractures created by mining in panels 5 and 6 may have induced physical recharge and an increase in pressure head to the coal bed. In addition, the overlying strata and coal bed may have been compressed when

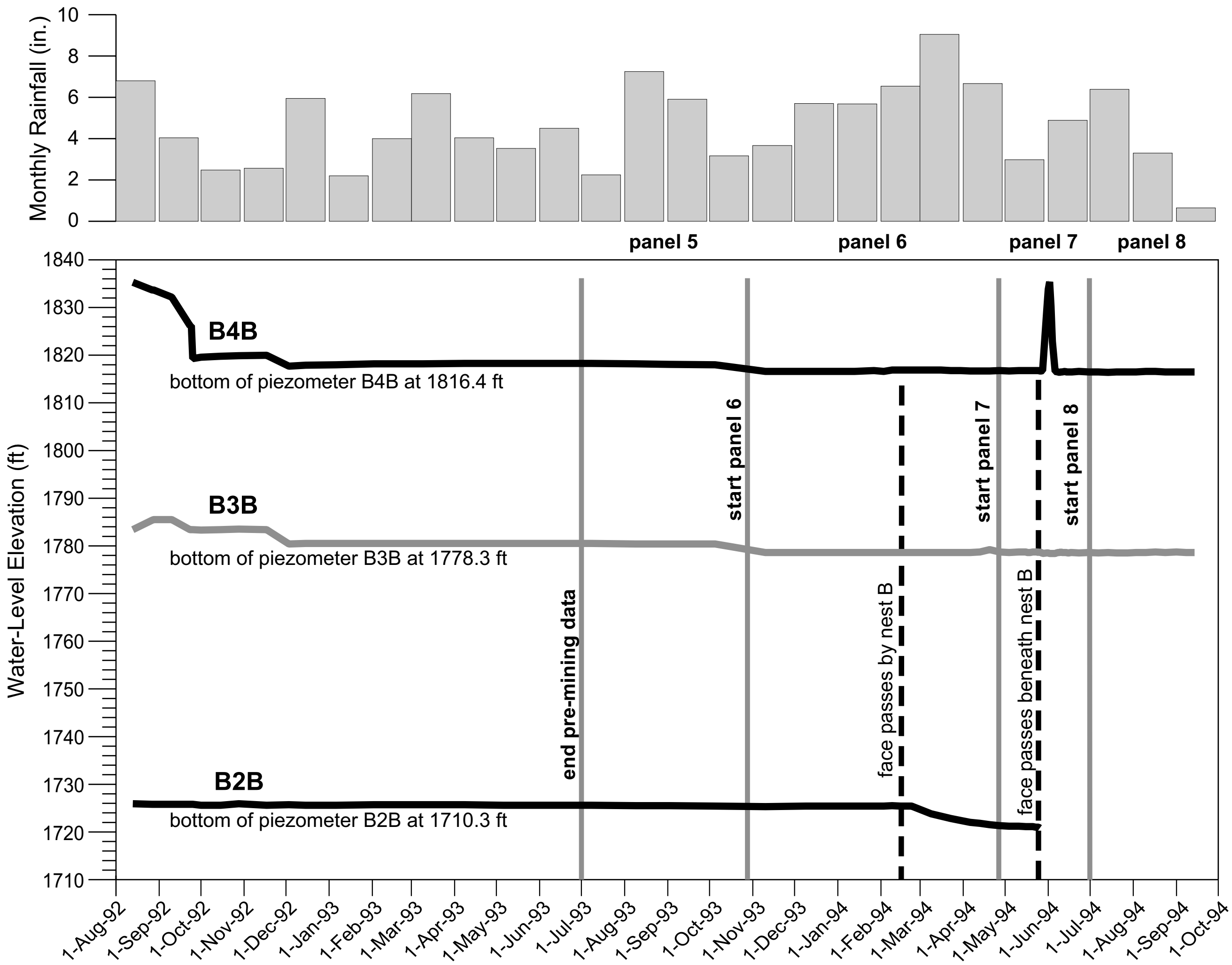

Figure 14. Hydrographs for piezometers B2B, B3B, and B4B, located between coal beds in the elevation-head zone.

these lithologic units in panel 7 were deflected downward toward the void created by mining in panels 5 and 6. This would help raise the hydrostatic pressure in the coal bed in panel 7 prior to mining of this panel. Similar but much less dramatic rises in water levels occurred in piezometers C2A and C2B in the sandstone unit above the Magoffin Member. This near-surface sandstone was most likely affected by fracture-enhanced recharge from the mining of panel 6 and the fact that the underlying Magoffin Member behaves like an aquitard.

The largest rise in water level occurred at site B, where piezometer B2A is located in the pressure-head zone (Fig. 15). Piezometers A2B (Fig. 15), C2B, and C2A (Fig. 16) had lesser rises in water level. These piezometers are located near the near-surface fracture zone and may have been influenced by it. Fractures in this zone would increase the intrinsic permeability, thereby reducing the rise in water level in these piezometers if the near-surface fracture zone does indeed extend down to their elevation.

Time-Domain Reflectometry

Time-domain reflectometry waveform readings taken during mining were compared with baseline TDR readings taken after the grout had cured, and before mining commenced in the watershed, on October 5, 1993. The dates when waveform readings were made and changes in TDR cables were noted are shown in Figure 20. All waveforms measured on February 15, 1994, were similar to those recorded on October 5, 1993. By March 2, 1994, however, new rises in the waveform (indicating partial cable breaks) were evident for cable A (at a depth of 78 ft) and cable B (at a depth of 353 ft). These depths correspond stratigraphically to shales adjacent to the Hazard coal. The mine face on panel 6

Table 3. Response of piezometer water levels in the elevation-head zone to mining.

Stratigraphic Interval	ridge-capping sandstone		coal beds			strata between coal beds		
Piezometer	B6A	B5B	B5A	B4A	B3A	B4B	B3B	B2B
Total Depth	92.0	149.2	178.8	226.7	270.0	205.2	243.1	311.0
Lithology	fractured sandstone	weathered sandstone	Hazard No. 8 rider	Hazard No. 8	Hazard No. 7	sandy shale	sandstone, sandy shale	fractured interbedded
Pre-Mining (Prior to 7/1/93)								
Range of water-level fluctuations	dry	2.3	1.0	3.2	0.8	0.6	0.1	0.3
Conductive strata	yes	yes	yes	yes	yes	no	no	yes
Panel 5 (5/3/93 through 10/20/93)								
Range of water-level fluctuations	dry	4.5	0.5	1.0	< 0.5	< 0.5	< 0.5	< 0.5
Water-level response—mine approach	none	down & up	none	none	none	none	none	none
Water-level response—mine retreat	none	down	none	none	none	none	none	none
Panel 6 (10/25/93 through 4/12/94)								
Range of water-level fluctuations	5.0	7.5	6.0	6.0	8.0	< 0.5	< 0.5	4.0
Water-level response—mine approach	none	down & up	up	up	up	none	none	none
Water-level response—mine retreat	up	down	down	up	up & fluctuate	none	none	down
Panel 7 (4/18/94 through 6/26/94)								
Range of water-level fluctuations	4.5	1.5	5.5	4.0	3.5	19.0	< 0.5	0.5
Water-level response—mine approach	down	fluctuate & dry	down & up	down	down	none	none	down
Water-level response—mine retreat	up	none	down	fluctuate	dry & up	up & down	none	failed
Panel 8 (6/30/94 through 9/14/94)								
Range of water-level fluctuations	0.5	dry	< 0.5	2.0	1.0	< 0.5	< 0.5	none
Water-level response—mine approach	none	none	none	up	none	none	none	none
Water-level response—mine retreat	none	none	none	down	none	none	none	none

Up: Water level in well went up relative to previously described state
Down: Water level went down relative to previously described state
Down & up: Water level went down then went up relative to previously described state
Fluctuate: Water level fluctuated, with no clear trend
Failed: PVC piezometer casing either broke or pinched closed

Table 4. Net effects from mining in the elevation-head zone.

Piezometer	*Net Response to Mining*
ridgetop	
B2B	down 3 ft and failed
B3A	down 3.5 ft
B3B	no change
B4A	no change
B4B	no change
B5A	down 5 ft
B5B	down 4 ft and went dry
B6A	up 4 ft

passed by both of these sites during this time. Water levels increased abruptly between February 15 and March 2 in associated piezometers completed in the Hazard coal zone (B2A and A2B). Subsidence cracks were first observed on March 2 on the ridge adjacent to site B, near the edge of panel 6. Calculations using the elevation difference between the Fire Clay coal (mined seam) and the Hazard coal (location of TDR changes), and the distance between the edge of panel 6 and the location of the TDR cables near the center of panel 7, indicate that rock-mass movement was at an angle of approximately 50° from vertical. This is much greater than the commonly reported values for angle of draw determined from the limit of measurable surface subsidence (25 to 30°).

A new rise in the waveform between April 13, 1994, and April 20, 1994, for cable A, at a depth of 159 ft, indicates a partially open cable. This depth corresponds to a dark-gray, sandy fireclay just below the Haddix coal. The partial break is almost certainly a delayed response to mining on panel 6, because mining

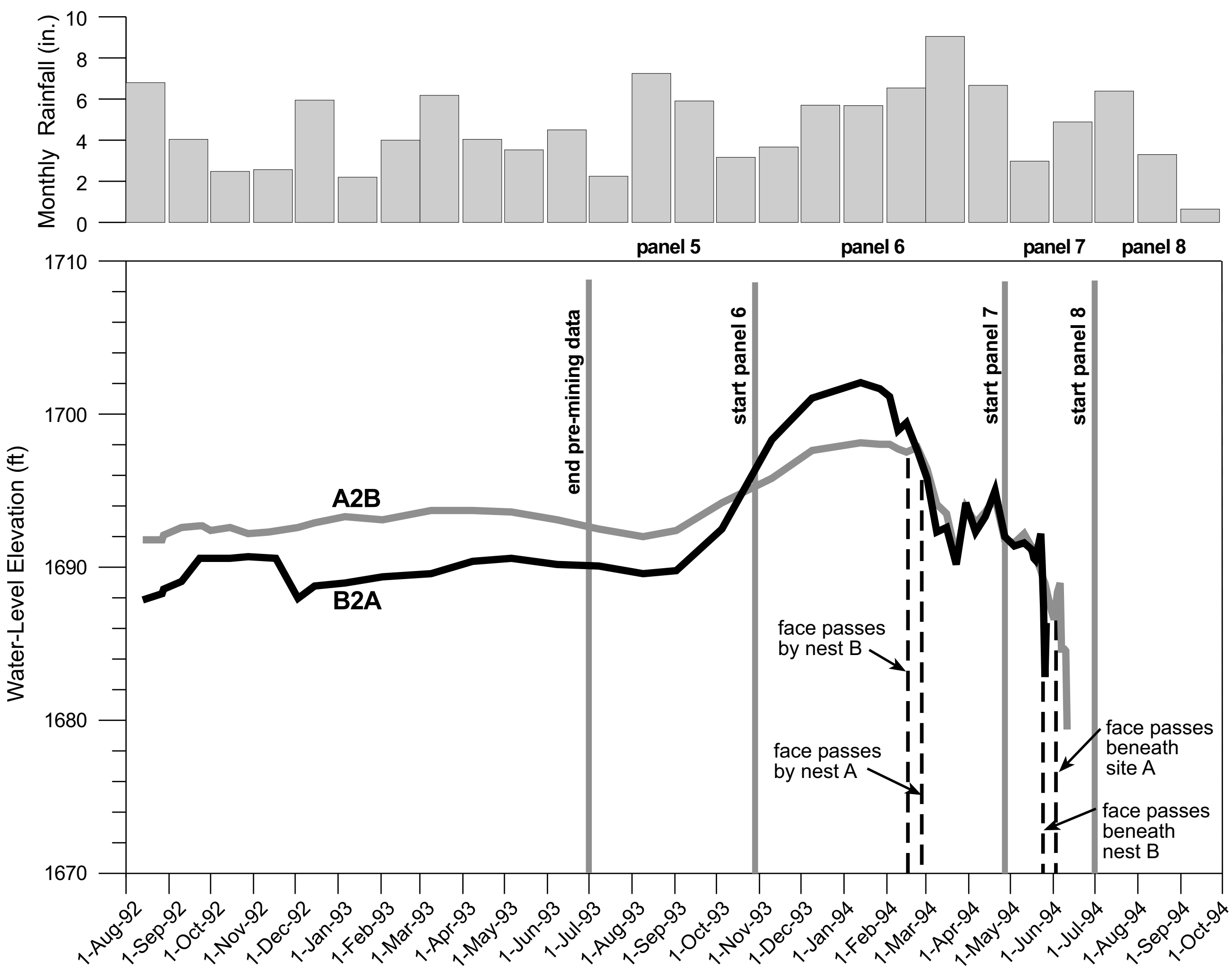

Figure 15. Hydrographs for piezometers A2B and B2A in the Hazard coal bed in the pressure-head zone.

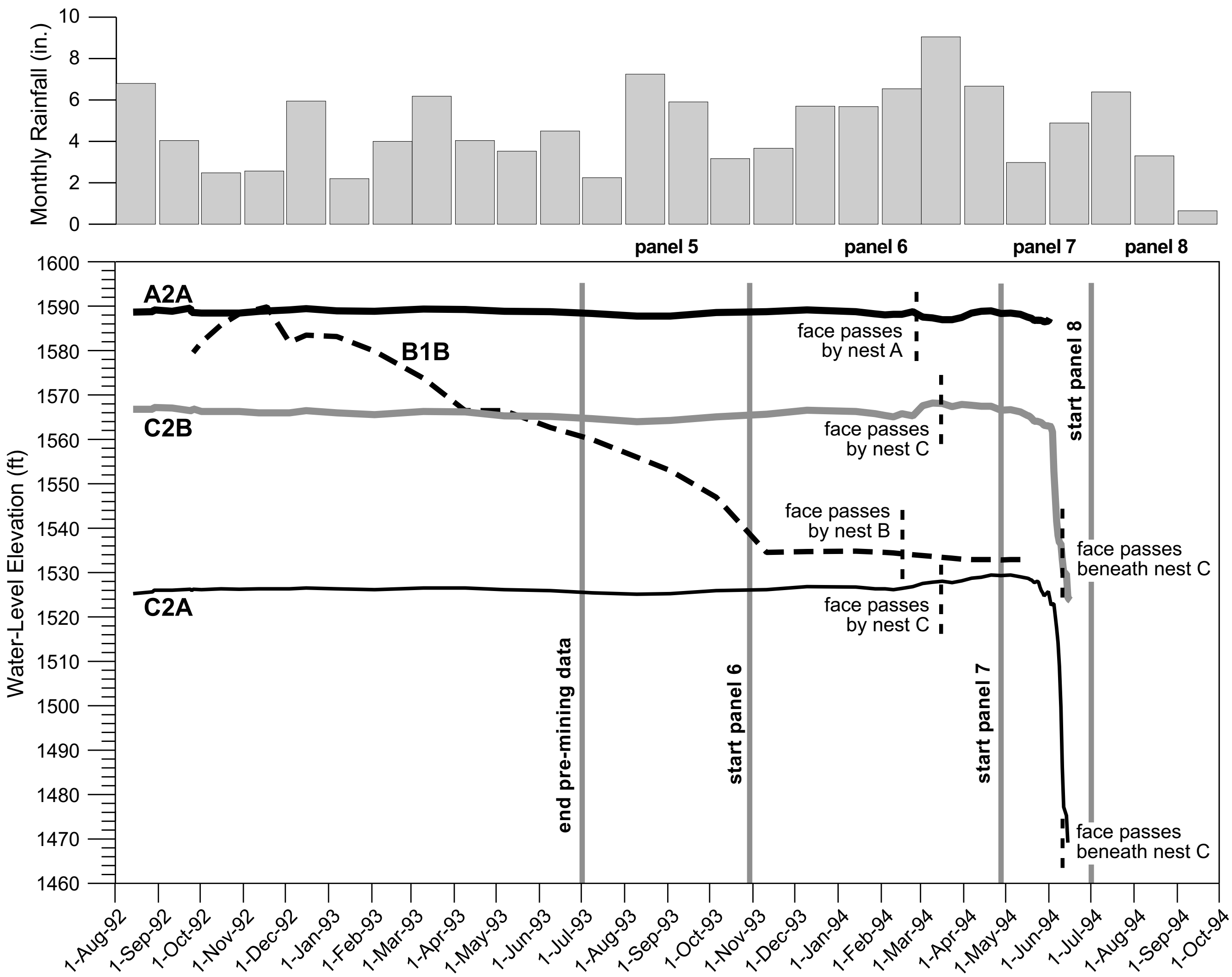

Figure 16. Hydrographs for pressure-head zone piezometers A2A, B1B, and C2B, located in the sandstone overlying the Magoffin Member.

did not commence on panel 7 until April 18, 1994, and the face for panel 7 was still more than 3,000 ft from site A on April 20. In addition, the waveform for cable B (located between the mine face for panel 7 and cable A) did not change during the same period. If this interpretation is correct, delayed rock strain from mining of panel 6 is indicated at an angle of rock-mass movement approximately 54° from vertical.

An additional change in the waveform for cable A, noted between measurements taken April 20 and April 27, 1994, indicated new crimping of the cable at a depth of 490 ft, in an interval of interbedded sandstone and shale (rippled). This is near the bottom of the cable and may be the result of deformation caused by the pipe that was used as an anchor at the base of the cable. This is also likely a delayed response to mining in panel 6, because during this period the mine face for panel 7 was still more than 2,800 ft away and the waveform for cable B did not change during the same period.

Between May 4 and May 11, 1994, cable B broke at a depth of 353 ft in the Hazard coal zone. The mine face for panel 7 would have been at least 1,115 ft away at that time, which results in an angle of rock-mass movement of at least 67° from vertical. Previous response to mining in panel 6 had also been observed at this depth.

Cable A broke at a depth of 78 ft in the Hazard coal zone between May 23 and May 24, 1994. The position of the mine face on panel 7 results in an angle of rock-mass movement of about 60° from vertical to the deformed zone.

The waveform for cable B indicated several changes as the mine face approached and passed beneath the site in panel 7. Between May 24 and 25, a new rise in the waveform (indicating a partially open cable)

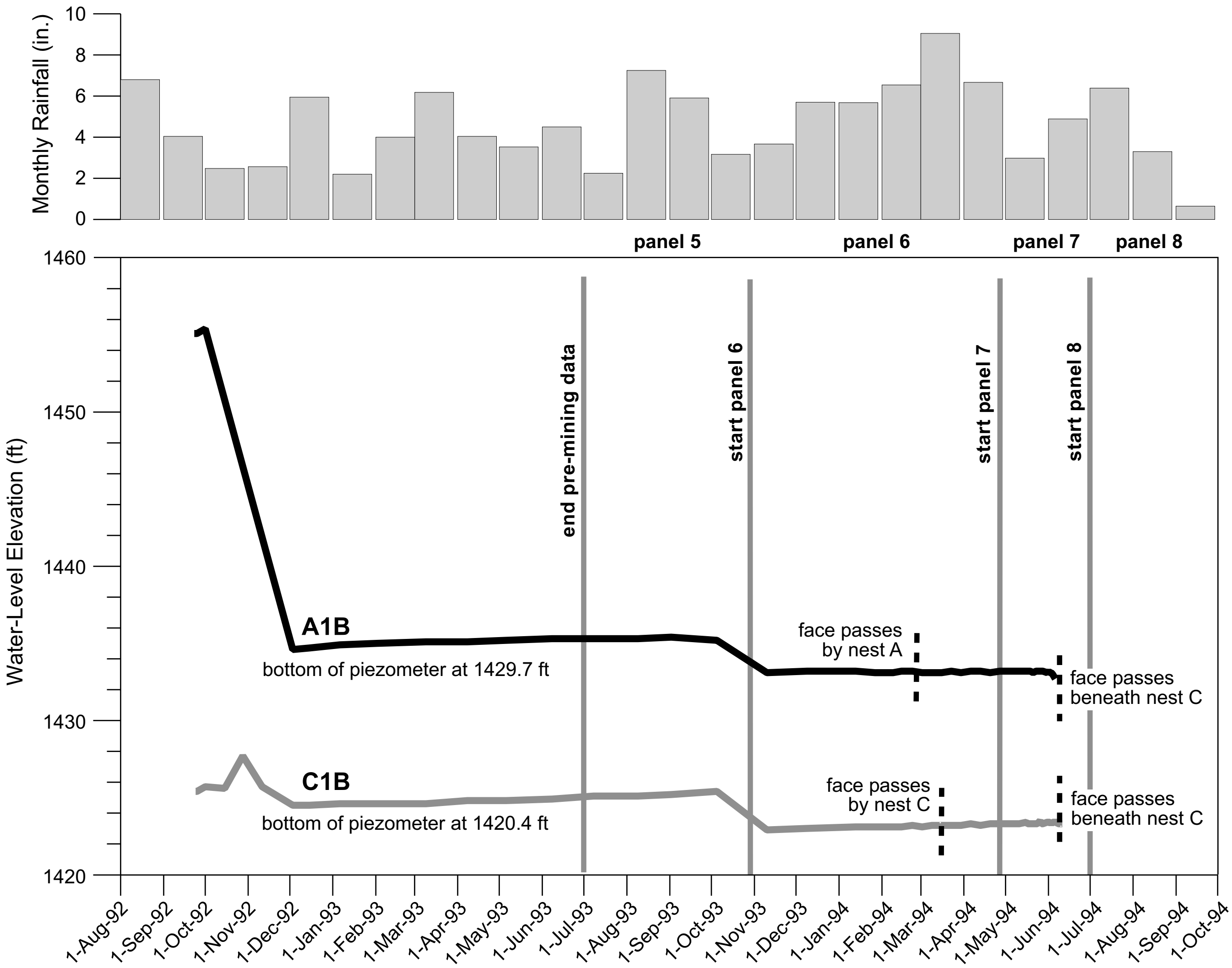

Figure 17. Hydrographs for pressure-head zone piezometers A1B and C1B, located in the Magoffin Member.

developed at a depth of 235 ft in a dark-gray, massive, sandy shale approximately 10 ft below the Hazard No. 8 coal seam; this results in an angle of draw of about 8°. On May 26, the cable broke at a depth of 53 ft. By this time, the mine face had passed beneath the site.

The first response to mining indicated on the waveform for cable C was between June 6 and June 7, 1994. The waveform suggests a partial break at a depth of 185 ft, which corresponds to a dark-gray, sandy fireclay beneath the Copland coal at the base of the Magoffin Member. At this time, the mine face was just over 300 ft away in panel 7. This indicates rock movement at an angle of rock-mass movement of 56° from vertical.

Between June 7 and 8, 1994, cable A broke at a depth of 13.5 ft. This depth corresponds to the bottom of the steel protective surface casing, and the break approximately coincided with the mine face passing beneath the site.

On June 9, the waveform for cable C indicated additional changes at a depth of 185 ft (just below the Magoffin Member). This deformation was at an angle of 46°, based on the position of the mine face in panel 7 at this time. By June 10, a new rise in the waveform (indicating a partial break) was observed at a depth of 115 ft. This corresponds to a sandy shale mudflow (Ferm and Melton, 1977) approximately 10 ft above the top of the Magoffin Member (angle of 11° to vertical). On June 11, cable C broke at a depth of 35 ft in gray sandstone with shale streaks, approximately 5 ft below the bottom of the steel surface casing. The mine face should have just passed beneath the site by this time.

Several patterns are evident in these TDR responses. Many of the changes were noted in zones corresponding to materials of relatively low strength (coal, underclay, shale). In other cases, cable damage occurred near boundaries between major rock units (such as at

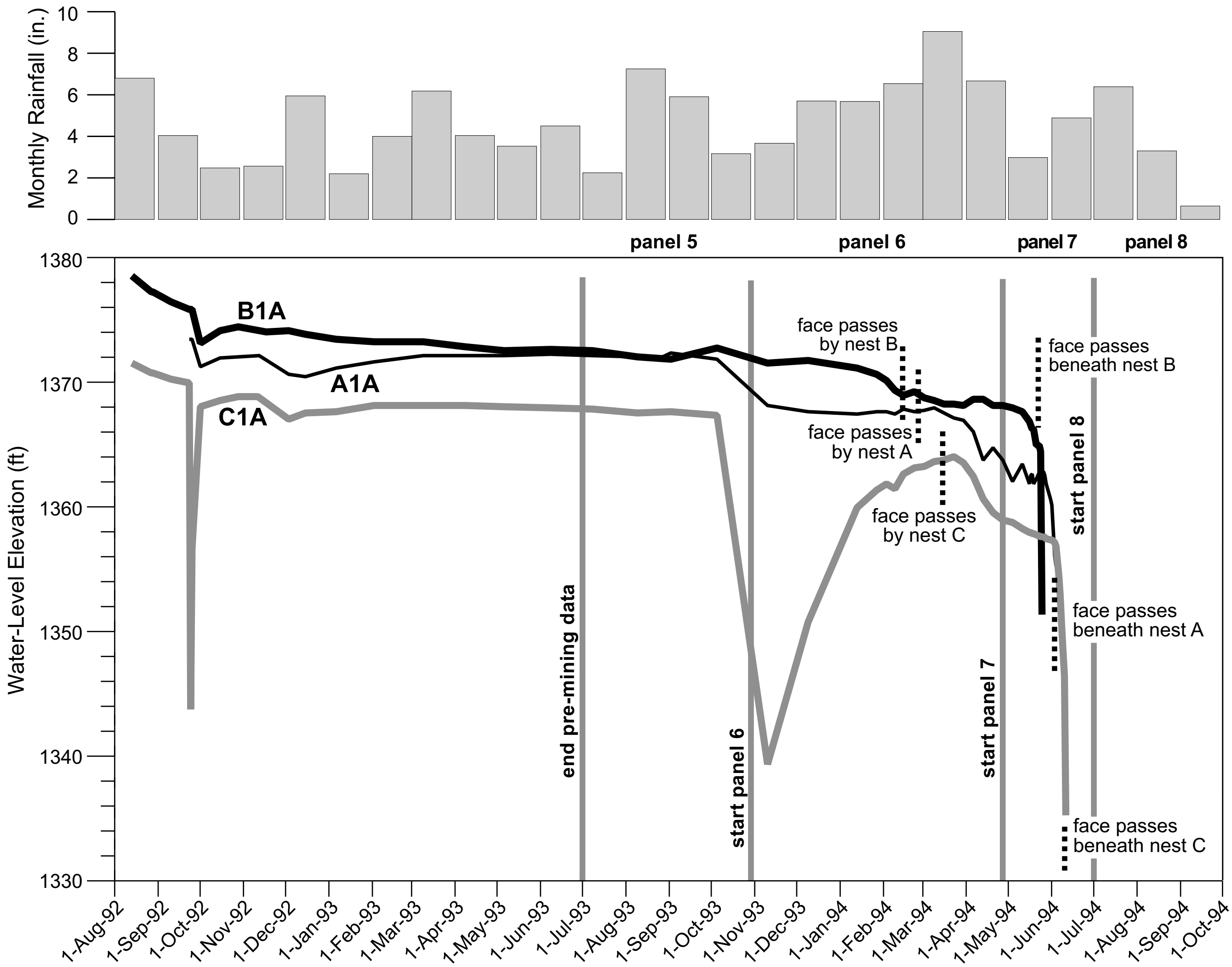

Figure 18. Hydrographs for pressure-head zone piezometers A1A, B1A, and C1A, located in the deep strata below the Magoffin Member.

the base and top of the Magoffin Member). Rock movement was commonly observed at angles between 50 and 60º to the panel edge or the approaching working face. This is approximately two times the values commonly reported for angle of draw, determined from the limit of measurable surface subsidence (commonly 25 to 30º). In some cases, hydrologic response was also noted in the zone undergoing deformation (as indicated by the changes in the TDR waveforms). Several of the responses interpreted as resulting from mining on panel 6 were delayed until several weeks after mining had passed by.

Surface-Water Response to Mining

The streamflow monitoring station at the outlet of the Edd Fork watershed operated throughout the mining period. The station had also been used earlier to assess pre-mining hydrologic conditions (Minns and others, 1995). Flow data show that summer storms produce sharply peaked runoff events. Surface runoff from winter precipitation also produces fast-rising stream runoff, but ground-water discharge tends to sustain the flow for longer periods.

Precipitation and runoff data were separated into water years (WY) so that comparisons could be made on a common basis. WY 1993 (October 1992 through September 1993) represents the period prior to mining. WY 1994 (October 1993 through September 1994) corresponds very nearly to the period of mining. Mining began in the watershed about August 23, 1993. Mining went beneath the flume about September 1, 1994, and exited the watershed about September 17, 1994.

Table 5. Response of piezometer water levels in the pressure-head zone to mining.

Stratigraphic Interval	Hazard coal		sandstone above the Magoffin Member				Magoffin Member		Hamlin coal		
Piezometer	A2B	B2A	B1B	A2A	C2B	C2A	A1B	C1B	B1A	A1A	C1A
Total Depth	86	355	488	234	71	131	328	174	684	415	260
Lithology	coal	coal	sandstone	fractured sandstone	fractured sandstone	sandstone & shale	shale	shale	coal & sandstone	coal & interbedded	coal & interbedded
Pre-Mining (Prior to 7/1/93)											
Range of water-level fluctuations (ft)	1.5	2.7	unknown	1.1	2.0	1.3	0.7	1.2	0.3	1.0	1.1
Conductive strata	yes	yes	no	yes	yes	yes	no	no	no	no	no
Panel 5 (5/3/93 through 10/20/93)											
Range of water-level fluctuations (ft)	2.5	3.0	unknown	1.0	1.0	1.0	0.5	0.5	1.0	0.5	0.5
Water-level response—mine approach	up	up	none	none	none	none	none	none	none	none	none
Water-level response—mine retreat	up	up	none	none	none	none	none	none	none	none	none
Panel 6 (10/25/93 through 4/12/94)											
Range of water-level fluctuations (ft)	12.5	12.0	2.5	1.5	3.0	4.0	0.5	0.5	3.5	4.5	unknown
Water-level response—mine approach	up	down	down	none	up	up	none	none	down	none	unknown
Water-level response—mine retreat	down	down	dry	down & up	none	up	none	none	down	down	down
Panel 7 (4/18/94 through 6/26/94)											
Range of water-level fluctuations (ft)	21.0	9.5	none	2.0	43.0	60.0	0.5	0.5	16.5	8.5	23.5
Water-level response—mine approach	fluctuate	fluctuate	none	down	down	down	none	none	down	down	down
Water-level response—mine retreat	up, down, & fail @ 1,679'	down, fail @ 1,674'	fail @ 1,588', vacuum then blow	fail @ 1,679'	fail @ 1,534'	fail @ 1,534'	fail @ 1,470', vacuum then blow	fail @ 1,482'	fail @ 1,677', vacuum	fail @ 1,564', blow then vacuum	fail @ 1,357', blow
Panel 8 (6/30/94 through 9/14/94)											
Range of water-level fluctuations (ft)	none	none	none	none	none	none	none	none	none	none	none
Water-level response—mine approach	none	none	none	none	none	none	none	none	none	none	none
Water-level response—mine retreat	none	none	none	none	none	none	none	none	none	none	none

Up: Water level in piezometer went up relative to previously described state
Down: Water level went down relative to previously described state
Up & down: Water level went up then went down relative to previously described state
Fluctuate: Water level fluctuated, with no clear trend
Unknown: Water level not stabilized; therefore effect is unknown
Fail: PVC piezometer casing either broke or pinched closed

Table 6. Net effects from mining in the pressure-head zone.	
Piezometer	*Net Response to Mining*
ridgetop	
B1A	down 21 ft and failed
B1B	dry and failed
B2A	down 6.5 ft and failed
valley side	
A1A	down 17.5 ft and failed
A1B	failed
A2A	down 1.5 ft and failed
A2B	down 22 ft and failed
valley bottom	
C1A	down 33 ft and failed
C1B	failed
C2A	down 66 ft and failed
C2B	down 42 ft and failed

Figure 21 shows the probability that flows of less than a given level will occur at the site, based on pre-mining (WY 1993) and during-mining (WY 1994) streamflow data. Higher flows occurred during the mining period than prior to mining in the watershed about 60 percent of the time. There was some base flow in the stream at all times during WY 1993, whereas during WY 1994 the stream was dry about 5 percent of the time.

Precipitation and runoff for the pre-mining year were 50.41 and 25.52 in., respectively. Precipitation and runoff during the mining period were 58.69 and 36.11 in., respectively. For the year, runoff as a percentage of precipitation was about 20 percent higher for the mining period (61.5 percent) than for the pre-mining period (50.6 percent).

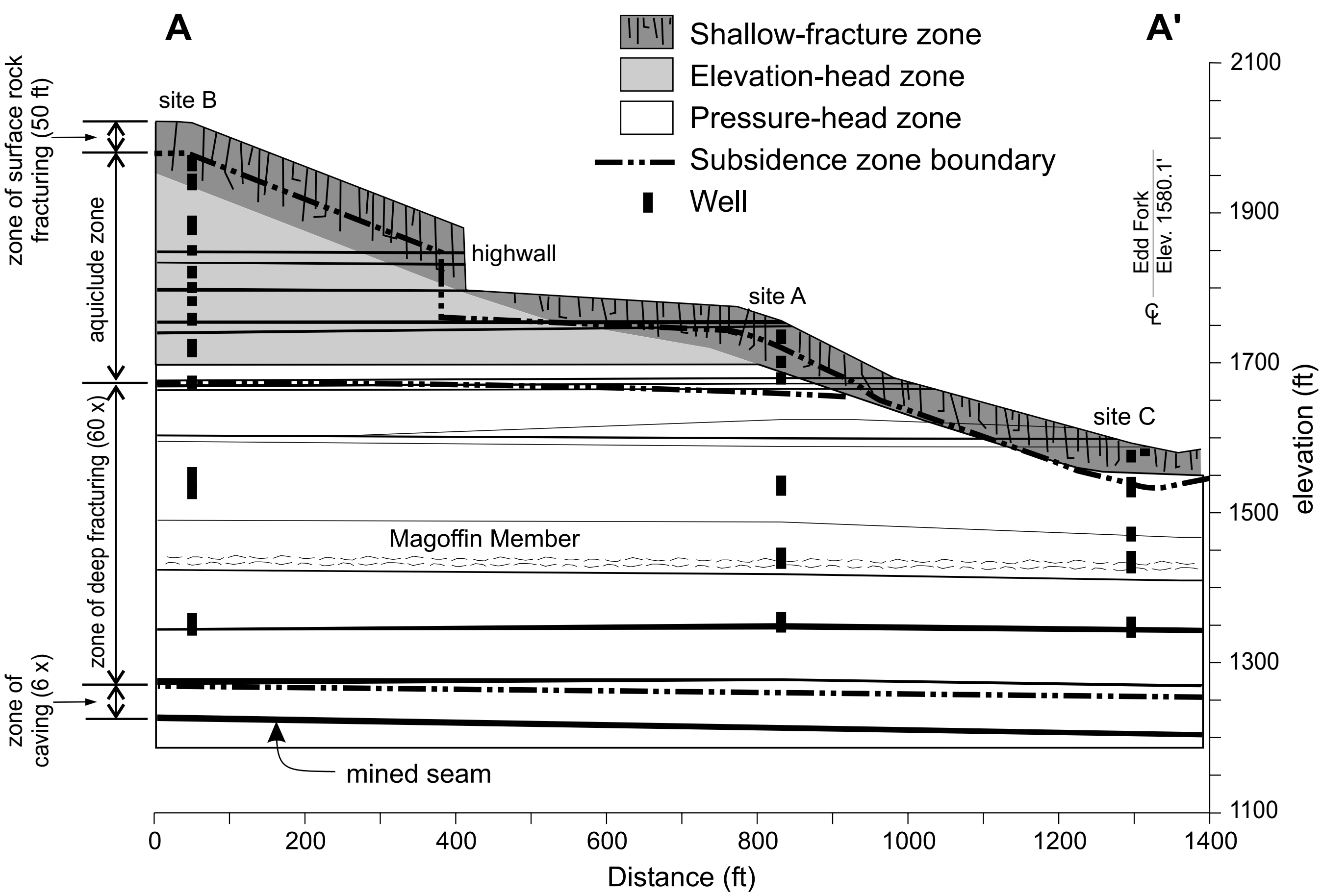

Figure 19. Approximate extent of subsidence zones in the Edd Fork watershed. Subsidence zones are those described by Coe and Stowe (1984).

Table 7. Summary of piezometer responses resulting from the passage of the mine face for each panel.

	Shallow-Fracture Zone			*Elevation-Head Zone*			*Pressure-Head Zone*				*Total*
Location	ridgetop	valley side	valley bottom	ridge-capping sandstone	coal beds	strata between coal beds	Hazard coal	sandstone above the Magoffin Member	Magoffin Member	deep piezometers in Hamlin coal	
Piezometer	B6B	A3A A3B	C3A C4A	B5B B6A	B3A B4A B5A	B2B B3B B4B	A2B B2A	A2A B1B C2A C2B	A1B C1B	A1A B1A C1A	
Total Piezometers	1	2	2	2	3	3	2	4	2	3	24
Panel 5 (1,450 ft away)				B5B: down			A2B: up B2A: up				3
Panel 6 (550 ft away)		A3A: dry		B5B: down B6A: up	B3A: up & fluctuate B4A: up B5A: down	B2B: down	A2B: down B2A: down	A2A: down B1B: down & dry C2A: up C2B: up		A1A: down B1A: down C1A: down	16
Panel 7 (undermined)	B6B: fail		C3A: fluctuate & dry	B5B: dry B6A: up	B3A: dry & up B4A: down & fluctuate B5A: fluctuate	B2B: down & fail B4B: up & down	A2B: down & fail B2A: down & fail	A2A: down & fail B1B: fail C2A: down & fail C2B: down & fail	A1B: fail C1B: fail	A1A: down & fail B1A: down & fail C1A: down & fail	20
Panel 8 (550 ft away)					B4A: down						1

Up: Water level in piezometer went up
Down: Water level went down
Up & down: Water level went up then went down
Fluctuate: Water level fluctuated with no clear trend
Fail: PVC piezometer casing either broke or pinched closed

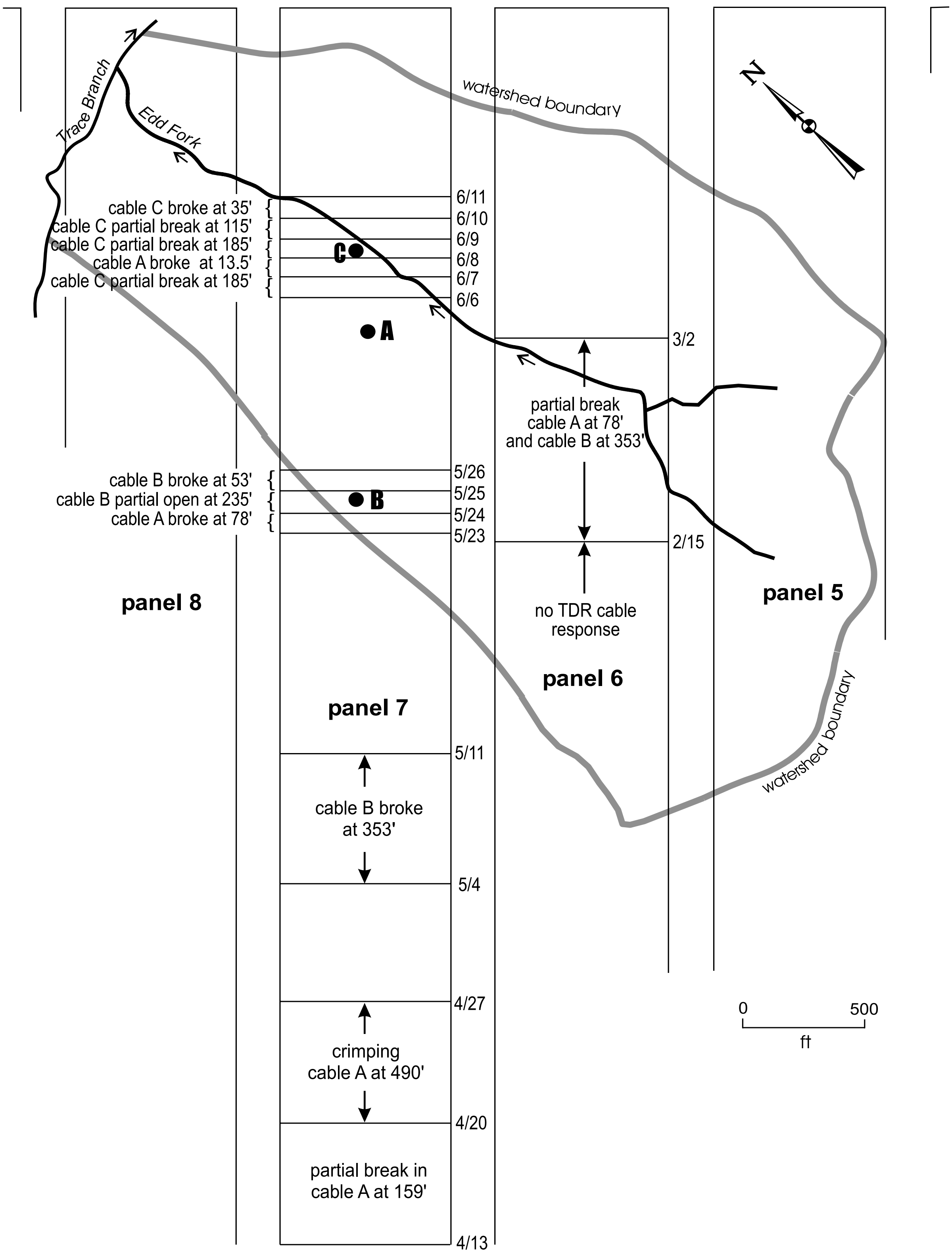

Figure 20. TDR cable responses in the Edd Fork watershed in 1994.

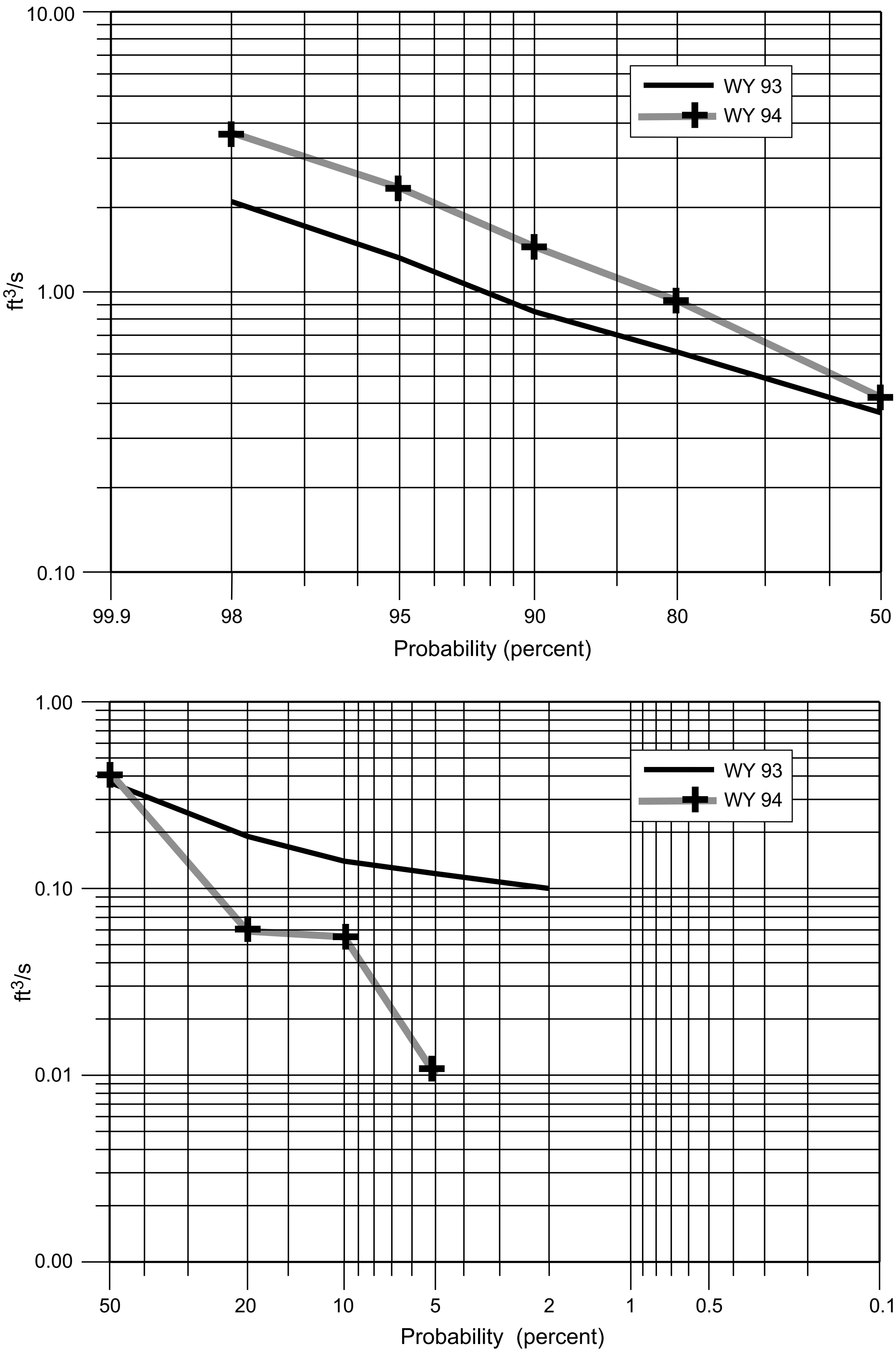

Figure 21. Probability of flows less than a given value for streamflow measured at the flume in Edd Fork for water years 1993 and 1994.

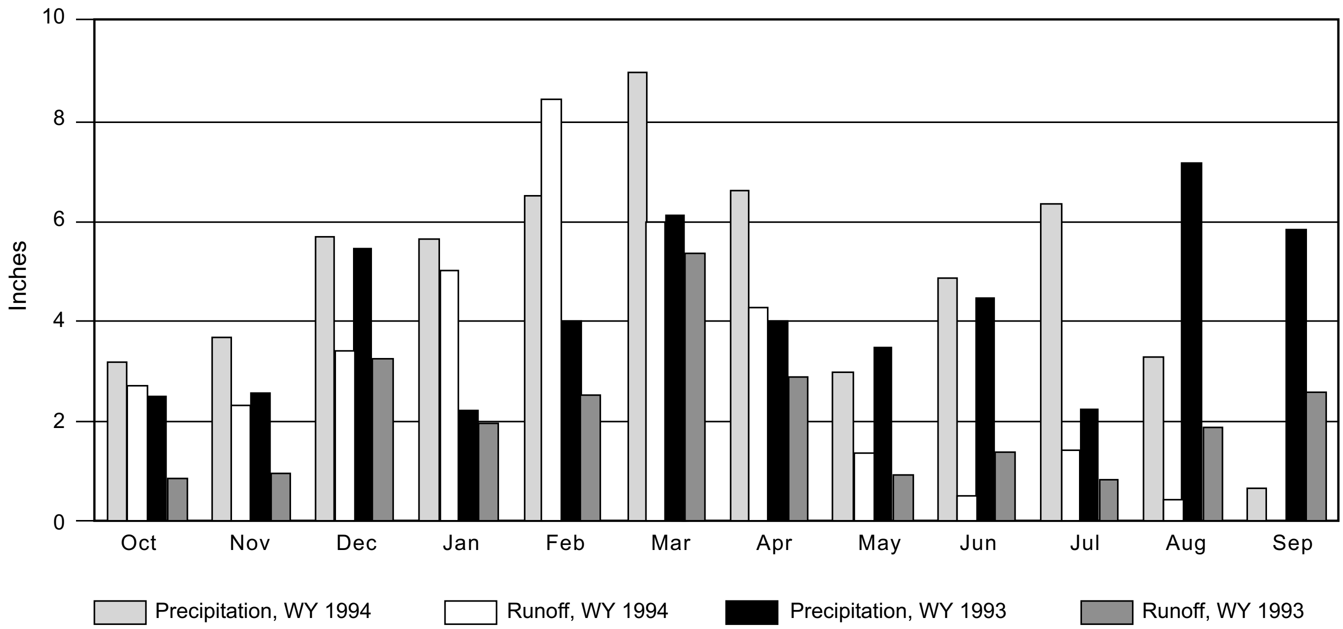

Figure 22. Precipitation and runoff during and before mining.

The higher relative runoff during the mining period most likely is because of seasonal differences (Fig. 22). Fall–winter precipitation (October–March 1993–94) during mining was 33.81 in., and there was 28.02 in. of runoff. Precipitation for the same period before mining (October–March 1992–93) was 22.93 in., and there was 14.96 in. of runoff. The winter of 1994 was relatively severe, with heavy snowfall and extended periods of frozen ground. This resulted in high runoff. Snowmelt in February provided more runoff than precipitation for the month.

The rainfall-runoff statistics for the spring–summer season during and before mining were not significantly different. Rainfall and runoff in the spring and summer during mining were 24.88 and 8.09 in., respectively. Rainfall and runoff for the same seasons before mining were 27.48 and 10.56 in., respectively.

Edd Fork went dry at the monitoring station for the first time during the study period on September 1, 1994, about the same time that the monitoring station was undermined. Except for some streamflow during one small rainfall, the stream remained dry for the entire month. This was also the month with the least precipitation, 0.65 in., so it is not clear whether the loss of base flow was the result of mining or dry weather. Monitoring after mining should clarify the issue.

Surface-Fracture Development

Surface fractures were observed along roads and in other nonvegetated areas as the active mine face advanced on panels 5, 6, and 7. Many fractures formed on spoil-covered ridgetops along the watershed boundary. Fractures were documented in roadways covered with shallow soil, and also were cut into bedrock. A fracture distribution map showing the approximate locations and orientations of fractures in the watershed is shown in Figure 23.

Surface fracturing was first observed on October 7, 1993, in the head of Edd Fork over panel 5, during a routine monthly visit. These fractures probably formed as mining progressed on panel 5 from early September through early October, but were not observed until mining was nearly completed on panel 5 in October. One notable area of fractures (see locations 3 through 6 on Figure 23) formed near the edge of panel 5 and the tailgate of panel 4. Approximately 1.5 ft of vertical displacement occurred in spoil material where the road curves along the undisturbed nose of the ridge. Large pits (10 ft wide by 15 ft deep) opened up, causing spoil material to be piped downward through large voids in the spoil. These features were repaired and the area has been stable for approximately 2 years.

Numerous tension fractures (see locations 1 and 2 on Figure 23) formed roughly parallel to ground slope along the head of an old hollow fill located on the east side of the watershed. The fill apparently moved downslope as the toe of the fill was undermined. The site, which was regraded to fill the fractures, has been stable for the past 2 years. Other minor spoil fractures that

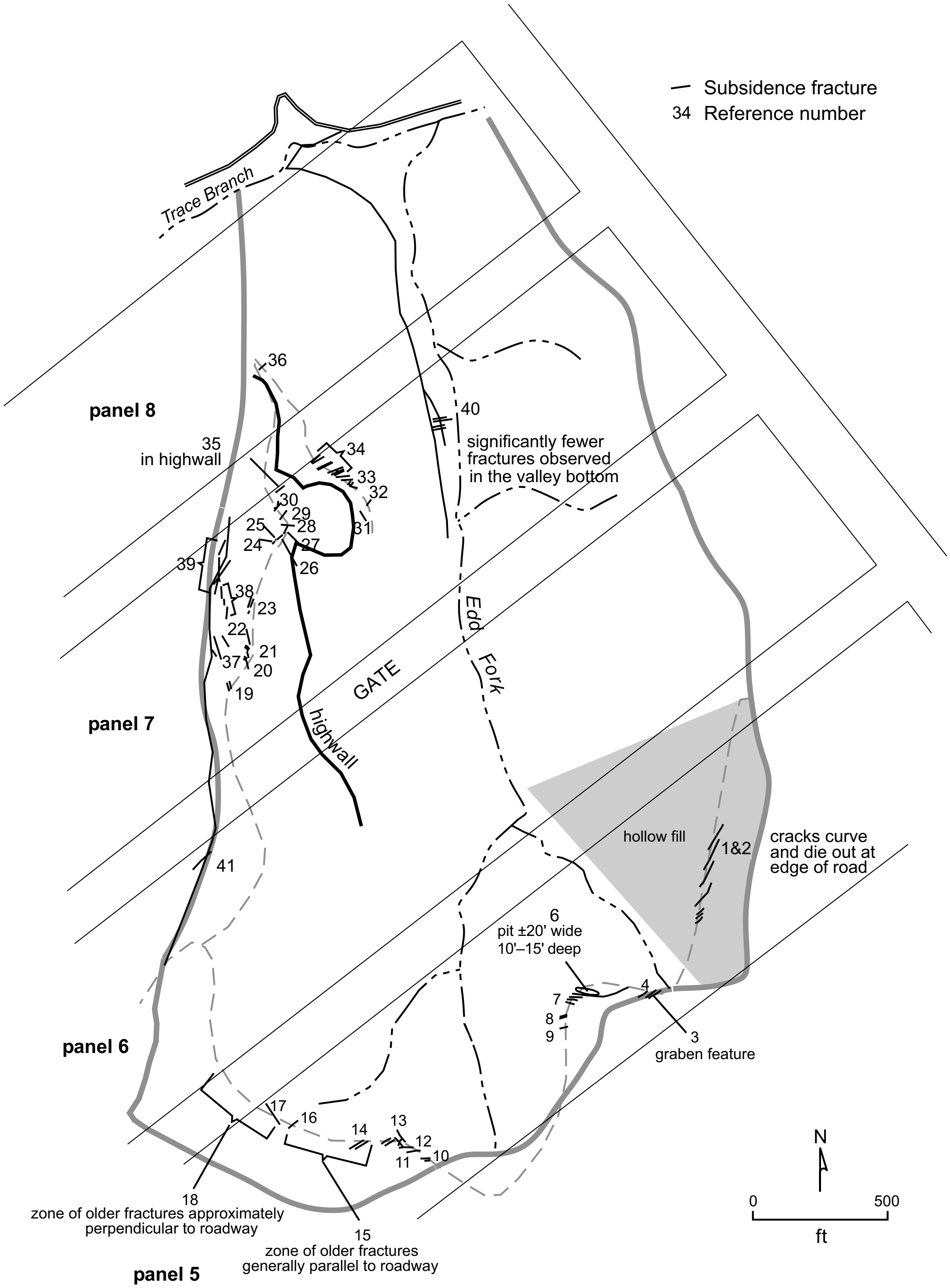

Figure 23. Approximate fracture locations and orientations mapped in the Edd Fork watershed.

formed along roads above panel 6 were generally subparallel to mining direction or ground slope.

Relatively few fractures were observed over panel 6, but this may be largely because of the limited exposure of open ground in the watershed. One fracture (see location 41 on Figure 23) was observed along the ridgetop on the road to site B on February 23, 1994. A slide several tens of feet wide was observed in the soil and colluvium the same day on the west side of the Edd Fork watershed over panel 6.

Fracture development was documented daily during undermining of panel 7, from about 10 days prior to the mine face entering the watershed until the completion of mining on the panel (see locations 37 through 39 on Figure 23). Fractures first appeared along the watershed boundary May 25 in the spoil near site B. Fractures continued to form and widen as mining advanced. Observable changes continued for approximately 13 days after fractures were first noted. The majority of these fractures were subparallel to the ridgeline. Ridgetop fractures generally widened in the downslope direction.

In addition to the development of surface cracks, the ground moved vertically relative to steel piezometer casings set at the same depth in the bedrock at site B. A lowering of the ground relative to the casings was initially observed the same day that cracks were first noted (May 25). The first day's displacement was a maximum of 0.5 in. and was accompanied by hairline cracks radiating from the casings. The majority of the displacement occurred over the next 13 days; minor changes appeared to continue for several days afterward, however. Maximum displacement was about 0.4 ft and occurred around piezometer B1. Displacement around the casings was not uniform, and there was no clear correlation between displacement and piezometer depth. Consequently, the observed ground movement is interpreted as representing a shifting of the unconsolidated spoil material.

Fracture development was observed in soil and bedrock along the access road to site A (see locations 19 through 35 on Figure 23). Fractures first appeared on May 31, 1994, about a week after mining passed beneath site B. Fracture formation continued gradually along this road for the next several days. On Monday, June 6, it was discovered that major fractures had developed over the weekend, to the extent that travel by vehicle was potentially dangerous. One fracture in the bedrock separated about 1.5 ft and was 13 ft deep (location 22 on Figure 23). Prominent joint faces were separated 2 in. in two locations, and in one case, the faces were offset about 2 in. Some fractures died out or terminated in fracture splays, and others continued into the rock outcrop along the road. Various fracture orientations indicate that fracture development was more complex than on the unconsolidated spoil-covered ridges, and was probably influenced by a combination of joint orientation, panel orientation, and ground slope.

Unlike at site B, ground movement relative to piezometer casings at site A was upward, and maximum displacement was about 0.05 ft. The ground was pulled away from the sides of the casing about 0.05 ft, indicating possible downslope soil movement. Fracturing was also noted in the valley bottom near site C. Numerous small hairline cracks formed, but no ground movement relative to piezometer casings was observed.

Fracture formation generally coincided with the passage of the longwall face, and appeared to occur rapidly. On one occasion, fractures appeared within a few hours. Most new fractures, however, were observed 12 to 16 hours after the previous reconnaissance (generally overnight). Fractures in spoil along ridges are commonly oriented parallel to slope. Fractures in rock may be controlled by a combination of joint patterns, panel orientation, and slope. Tension fractures subparallel to panel orientation were most commonly observed near the panel edges. Fractures were more common on ridges and valley sides than in the valley bottom. Ridgetop and valley-side fractures tended to widen, indicating downslope movement.

Summary

Twenty-four piezometers were installed at varying depths over a longwall mine in a small eastern Kentucky watershed characteristic of the steep topography and geology of the Appalachian Plateau region. Thickness of overburden above the mine in the watershed ranges from 800 ft on ridgetops to 300 ft in the valley bottoms. The deepest piezometers were located about 150 ft above the mined seam. Water levels were monitored as mining approached and retreated from the panels being undermined, as well as when adjacent panels were mined. Streamflow in Edd Fork, which drains the watershed, was also evaluated.

Hydrologic response to mining was varied, as would be expected in a complex flow system, and because the entire surface area subsided approximately 4.5 to 7.5 ft. As a result of this subsidence, water levels in piezometers are referenced to the stratigraphic intervals they monitored, and not to actual elevation. Responses to mining in adjacent panels 5 and 6 were recorded in 16 different piezometers. Water levels in five piezometers (B6A, B3A, B4A, C2A, and C2B) were higher than pre-mining levels immediately after mining of panel 6 was completed. Water levels in the remaining 11 piezometers generally were lower after mining of panel 6 was completed (see Table 7).

Undermining of the piezometers had the most widespread and dramatic effects; 20 of 24 piezometers responded in some manner. Fifteen piezometers either had lower water levels or went dry, and 13 of the 24 piezometers failed structurally. The only piezometer with a higher water level after mining was piezometer B6A, a piezometer in the shallow-fracture zone, located in the ridge-capping sandstone. This piezometer was dry until the mine face passed by on the adjacent panel 6. Only one piezometer responded to mining in panel 8, but the majority of the piezometers had already failed or their water levels had declined as a result of previous mining in panels 6 or 7.

Piezometers in which water level changed during mining of panel 7 were in conductive coal beds or in fractured intervals. Piezometers completed in relatively impermeable strata such as shale (the Magoffin Member, for example) showed no observable water-level changes.

All but one of the 13 piezometers that failed were completed in holes that apparently extended into the zone of deep fracturing created by the mine void. Piezometer B6B, the exception, was completed near the surface in sandstone. Indications are that the zone of deep fracturing extends approximately 450 ft upward from the mine void (60 times the extracted thickness), which is near the upper end of the range for documented deep fracturing reported by Coe and Stowe (1984). One stratigraphic interval in which piezometer breakage was apparently consistent was the Hazard coal bed (piezometers B1A, B2A, A2A, and A2B), which is about 425 ft above the mined-out seam. Five of the 13 piezometers that failed were directly connected to the active mining void in the Fire Clay seam (Hazard No. 4), as evidenced by vacuums forming at piezometer heads after mining.

The Hazard coal zone, a 10-ft-thick zone of multiple coal beds, is apparently susceptible to mining-induced stress and strain. Partial breaks in the TDR cables at sites A and B were documented in the Hazard coal zone as the mine face passed by on panel 6. Water levels in the two piezometers completed in the same zone (A2B and B2A) also declined significantly during the period. Panel 7 mining resulted in cable breaks in front of the advancing face in the Hazard coal zone at sites A and B when the face was about 1,000 ft away from site A and more than 1,100 ft from site B. Piezometer casing broke at the depth corresponding to the Hazard coal in four piezometers (A2A, A2B, B1A, and B2A) as mining passed under each site. TDR cables broke in two intervals. Breakage in the Hazard coal zone, the only zone where complete breakage was recorded at depths greater than 50 ft, occurred well in advance of the active face at corresponding angles of rock-mass movement from 60 to 70° of vertical. All three TDR cables also broke within 50 ft of the surface as mining passed under each site. The shallowest piezometer at site B (B6B) broke at a depth of about 50 ft as mining passed underneath the piezometer. Shallow rock breakage (less than 50 ft, which corresponds to the zone of surface fracturing) was associated with undermining, whereas breakage in the weak coal zone occurred well in advance of the mine face.

The surface-water monitoring station on Edd Fork overlies panel 8. No distinct response was detected during mining in panels 5 through 7. Edd Fork went dry for the first time as the active face undermined the stream. Because of the lack of rainfall during that period, the immediate effects of mining on the surface water in the watershed are unclear.

Surface cracks were observed along roads and on bare areas of spoil in the watershed. These fractures appeared abruptly as the mine face passed. Measured fractures ranged from a few feet in length to nearly 100 ft. Some fracture traces that passed from bare areas into heavy vegetation and were no longer visible may be longer. Fracture widths varied from hairline cracks to spoil collapses that were 20 ft wide. Fractures were generally subparallel to panel direction or parallel to ground slope.

Impacts of Longwall Mining on Water Resources

Data derived from piezometers and time-domain reflectometry support the validity of a general subsidence model developed by Coe and Stowe (1984). Above the totally caved zone is a zone characterized by intensive fracturing, in which piezometers commonly fail. Water levels in this zone fall rapidly, and connection to the mine is possible. Water levels will probably not recover until the mine is sealed. An aquiclude zone develops in the ridges where there is sufficient overburden over the mine. Integrity of strata is generally maintained, and water-level effects should be least noticeable in this zone. Effects of mining in the zone of surface-rock fracturing, which occurs within approximately 50 ft of the ground surface, are most variable because strata are susceptible to both recharge and dewatering effects as fractures develop.

Water-level responses in areas adjacent to active mining are more related to the complex ground-water flow system than to a simple angle of hydrologic influence measured from a panel edge. Conductive strata such as coal beds were affected by mining in adjacent panels from as far away as 1,450 ft. Responses to mining were much more common in panel 6, however, which was only 550 ft away. In confined strata (generally below drainage), water-level effects may occur rapidly over this distance. Water-level changes in a confined system are attributed to relatively instantaneous hydrologic pressure changes, which can be transmitted rapidly over large distances. These effects would be most noticeable in conductive strata such as coals and in well-connected fracture systems. In unconfined strata (largely above drainage), water must physically move through rock openings, and as a result, effects are dependent on the rate and distance the water travels. Effects are likely to be delayed, compared to effects observed in confined strata.

Surface fractures that develop as a result of mining provide direct avenues for water infiltrating from the surface, and can greatly increase vertical recharge. Increased fracture permeability resulting from widening of existing fractures can also greatly enhance vertical recharge. Yield to piezometers could increase as a result of additional storage and recharge. Undesirable effects include dewatering of shallow strata because of fractures, rapid introduction of surface contaminants into the ground-water system, and increased discharge to surface seeps, which may create slide hazards. Filling surface fractures in a timely manner may prevent rapid infiltration caused by direct runoff entering fractures.

Because subsidence caused by longwall mining alters the long-term equilibrium of the ground-water flow system, water-quality changes during and after mining should be expected. Fractures expose fresh surfaces, which may increase iron, manganese, and sulfate concentrations until these newly created surfaces heal over, a process that may take years or decades. Mixing of naturally occurring water types may also occur as a result of mining. Because physical changes were noted 1,450 ft away from the active mine face, water-quality changes may be expected to occur a similar distance away.

FUTURE RESEARCH

The post-mining phase of this project began in October 1994. Long-term data will be collected so that water-level recovery and chemical changes in the system can be evaluated. Water-quality issues will be addressed in the post-mining phase if water levels recover enough for reliable samples to be obtained.

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APPENDIX A:
KGS DATA REPOSITORY RECORD NUMBERS

Piezometer No.	*Record No.*
A1A	13856
A1B	13857
A2A	13858
A2B	13859
A3A	13860
A3B	13861
B1A	13862
B1B	13863
B2A	13864
B2B	13865
B3A	13866
B3B	13867
B4A	13868
B4B	13869
B5A	13870
B5B	13871
B6A	13872
B6B	13873
C1A	13874
C1B	13875
C2A	13876
C2B	13877
C3A	13878
C4A	13879
C5	Unassigned
C6	Unassigned

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Information Circular 5 (ser. 11): Quality of surface water in Bell County, Kentucky, by R.B. Cook, Jr., and R.E. Mallette, 1981, 11 p.

Information Circular 37 (ser. 11): Water quality in the Kentucky River Basin, by D.I. Carey, 1992, 56 p.

Information Circular 44 (ser. 11): Quality of private ground-water supplies in Kentucky, by D.I. Carey and others, 1993, 155 p.

Information Circular 46 (ser. 11): Impact of riparian grass filter strips on surface-water quality, by A.W. Fogle and others, 1994, 14 p.

Information Circular 52 (ser. 11): Ground water in the Kentucky River Basin, by D.I. Carey and others, 1994, 67 p.

Information Circular 60 (ser. 11): Ground-water quality in Kentucky: Nitrate-nitrogen, by P.G. Conrad and others, 1999, 4 p.

Information Circular 1 (ser. 12) Ground-water quality in Kentucky: Fluoride, by P.G. Conrad and others, 1999, 4 p.

Map and Chart Series 10 (ser. 11): Mapped karst ground-water basins in the Lexington 30 x 60 minute quadrangle, by J.C. Currens and J.A. Ray, 1996, scale 1:100,000

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Report of Investigations 11 (ser. 11): Hydrogeology and ground-water monitoring of coal-ash disposal sites in a karst terrane near Burnside, south-central Kentucky, by S.M. Hutcheson and others, 1997, 21 p.

Report of Investigations 12 (ser. 11): Fresh-water aquifer in the Knox Group (Cambrian–Ordovician) of central Kentucky, by J.A. Kipp, 1997, 15 p.

Report of Investigations 13 (ser. 11): Impact of topographic data resolution on hydrologic and nonpoint-source pollution modeling in a karst terrane, by A.W. Fogle, 1998, 22 p.

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